



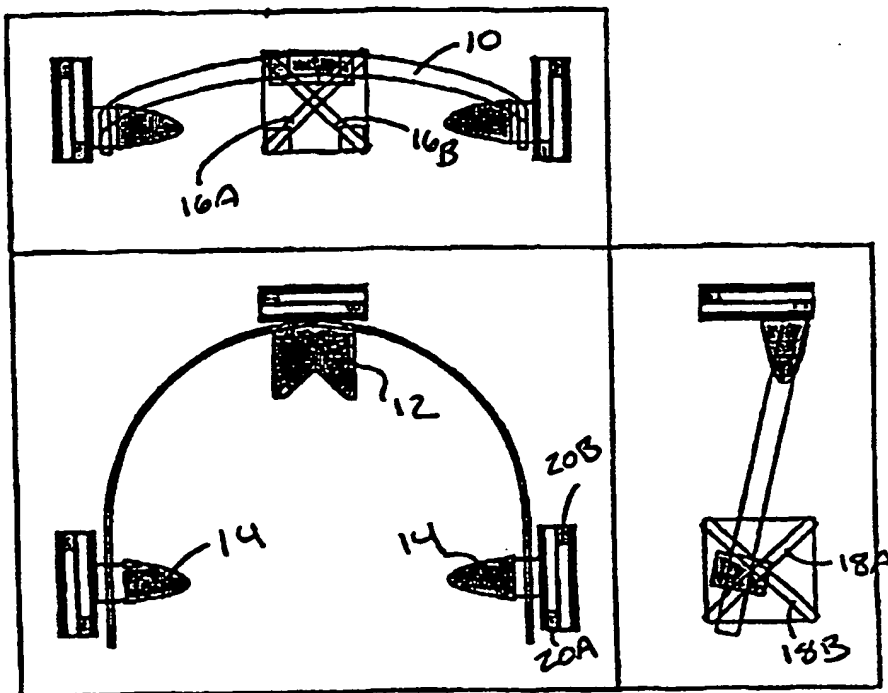
## INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

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(54) Title: VERSATILE STEREOTACTIC DEVICE AND METHODS OF USE

## (57) Abstract

A stereotactic device for use with an image, which permits an imaging scan to be taken with reference to a personal coordinate system (PCS) that is independent of a machine coordinate system (MCS). Methods using the device to obtain imaging scans (28) are described such that the imaging scans are superimposing even if taken at different time periods using the same or a different image. The device comprises a frame (10) that can be reproducibly positioned on a subject, and which is equipped with non-invasive affixing means (12, 14) and localizing means (16A, 16B, 18A, 18B, 20A, 20B) that provide the PCS. The device and method steps are particularly well suited for routine initial or follow-up examinations, pre-surgical planning and post-surgical evaluation.



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**VERSATILE STEREOTACTIC DEVICE AND METHODS OF USE**

5

Cross Reference to Related Application

This application claims the priority date of Provisional U.S. Application Serial No. 60/002,497, filed August 18, 1995, the disclosure of which is incorporated in its entirety by  
10 reference herein.

1. Field of the Invention

The invention pertains to a versatile stereotactic device useful in a number of methods, including numerous modes of  
15 medical imaging. More particularly, the device and methods of the present invention relate to a non-invasive stereotactic method of reproducibly imaging portions of a patient's body, such as the patient's head and portions of the patient's spine in the proximity of the head. Thus, imaging modalities,  
20 including magnetic resonance (MR) imaging, magnetic resonance spectroscopy, computer-aided tomography (CT), positron emission tomography (PET), single photon emission computed tomography (SPECT), electroencephalography (EEG) or magnetoencephalography (MEG) and the like can be used to monitor, diagnose, or detect  
25 pathologic conditions and to follow their development, progress, arrest, or remission. The device and methods of the invention are especially applicable to permitting more routine head examinations, pre-surgical planning and providing post-surgical evaluations and prognoses.

30

2. Background of the Invention

In head examinations involving magnetic resonance imaging, computer-aided tomography and other such techniques, it is desirable to have a well-defined, reproducible coordinate  
35 system to record and/or compare the locations and sizes of lesions, tumors and other structures of interest. Though there

are a number of known devices and techniques for potential application to these types of examinations, these known devices and techniques are generally not suitable for "routine" office examinations, in which factors such as ease of use, speed of use, comfort, cost, accuracy and reproducibility are of major consideration. Indeed, existing devices are often heavy, unwieldy, cumbersome and require that the devices be affixed to the subject using pins, screws, bolts, brackets, staples and the like.

Several methods have been proposed to find the relative position of a scan "slice" by using anatomical landmarks. In these methods, the size and position of predetermined anatomical structures, such as the lateral end of the internal auditory canal, are used as reference points to help locate and compare lesions and other features of interest. See, e.g., Tan, K.K. et al., in *J. Neurosurg.* (1993) 79:296-303. A problem with this technique, however, is that the image resolution in the scan slice direction (i.e., the z-direction) is poor compared with the resolution in the scan in-plane (x-y direction). Because of this poor resolution, it is difficult to make precise positional determinations. Moreover, these methods also require a degree of anatomical knowledge which may strain the capabilities of the average MR technologist.

As an alternative, the art has developed devices, such as frames and "halos," to facilitate positioning for stereotactic surgery. These devices are rigidly affixed to the patient being imaged and to an imager platform and provide reference points or lines to facilitate the determination of the orientation of the patient's head. See, e.g., U.S. Patent No. 4,341,220, which discloses a stereotactic surgical frame with fiducial plates that surround the patient's head in the fashion of a boxer's headgear and which provides several non-collinear fiducial points in cross-sectional scans. Most stereotactic frames are fixed to the patient's skull directly,

usually by bolts or screws, as noted previously. Clearly such methods are not suitable for "routine" office examinations.

So-called non-invasive, stereotactic devices have also been described. The Gill-Thomas stereotactic frame, which is  
5 based on the Brown-Roberts-Wells neurosurgical frame, was designed to be used for a series of stereotactic radiotherapeutic operations. See, Graham et al., in *Radiotherapy and Oncology*, (1991) 21:60-62. This device requires that it be affixed to the patient by a block, tailored  
10 for individual patients.

Another device, designed by Laitinen et al., is fixed to the patient by means of a nasion support and two ear plugs. See, e.g., Laitinen et al., in *Surg. Neurol.* (1985) 23:559-566 and U.S. Patent No. 4,617,925. However, this device is then  
15 affixed to the imaging couch or table. Hence, this device is able to permit reproducible scans only by relying on the fixed position of the patient against the couch or table with respect to the machine coordinate system. Again, affixing the patient to the machine may makes the patient uncomfortable during the  
20 scan. See, also, U.S. Patent No. 5,330,485, disclosing a cerebral instrument guide frame that rests on the bridge of the nose (i.e., about the nasion) and which contains plugs for insertion into the external ear canals.

Stereotactic devices are typically fashioned from  
25 precision aluminum alloy and are very expensive for all except non-routine use. Moreover, it is usually cumbersome and time consuming to affix these devices to the patient, adding to their unsuitability for routine examinations.

The state of the art suggests that stereotactic devices  
30 be equipped with radiographic markers that are visible in scans of a patient's head. For example, U.S. Patent No. 4,923,459 discloses a stereotactic frame that also includes radio-opaque rods arranged in the configuration of the letter "N" to facilitate localization of a surgical target. U.S. Patent No.  
35 4,608,977 discloses a helmet-like, stereotactic frame that

includes such N-shaped "localizing" rod to facilitate the determination of the location of a CT scan cross-section. Likewise, U.S. Patent No. 4,638,798 discloses a halo-like stereotactic frame that has a ring with a plurality of pins of  
5 differing lengths extending therefrom. The relative location of a scan can be determined from the relative location of the ends of the pins.

Though such devices can be used to determine the location of a head in x-y space, and to determine the relative location  
10 of each imaging "slice," they do not permit the position of a head to be fully determined, e.g., as where the head is tilted in the imaging plane.

In addition to the limitations described above, the prior techniques are not generally suitable for direct alignment of  
15 images obtained from different imaging modalities. That is, to permit the direct comparison of images obtained from different imaging modalities, say MR and CT, the patient must be re-aligned precisely with respect to the two machine coordinate systems. Alternatively, a correction can be made using image  
20 processing techniques after a second or subsequent scan has been taken. However, image processing has the drawback in that the resolution of the processed image is dependent on the quality of the scan data set. It would be desirable to alter a scan in real time such that scans from different modalities  
25 can be compared directly without the need for image processing.

In each of the known devices and methods, the anatomical coordinates of the patient are fixed in relation to a reference coordinate system, that is the machine's coordinate system. Thereafter, the machine's coordinate system is used as the  
30 reference coordinate system for each subsequent scan. Because of the difficulty in reproducing the machine coordinate system or because different machines are invariably associated with different, incompatible machine coordinate systems, it has not before been possible to relate directly scans from different  
35 imaging modalities. Moreover, it is not always possible to

align directly scans from the same imaging modality (e.g., MR imagers) when comparing images obtained from machines made by different manufacturers.

It would thus be desirable to have a device and method whereby the reference coordinate system is independent of the machine or imaging modality. It would be desirable, moreover, to use a reference coordinate system "personal" to the patient as the reference coordinate system and, where possible, have the machine's coordinate system fixed or adjusted relative to that of the patient to provide for scans that are reproducible, compatible and superimposable in the same or different imaging modalities. A system that enables the taking of imaging scans under such a patient reference or "personal" coordinate system would be of great utility and would be deemed a significant advancement in the art.

In view of the foregoing, it is an object of the invention to provide improved devices and methods of non-invasive, repetitive, radiographic examination of a subject, particularly of the subject's head.

A further object of the invention is to provide such devices and methods that are readily amenable for use in "routine" examinations, as well as for surgical planning and follow-up.

A still further object of the invention seeks to provide improved devices and methods of stereotaxis (both invasive and non-invasive), which are low-cost, easy to use, comfortable and which provide accurate and reproducible results.

Yet another object of the invention relates to improving methods and apparatuses that can determine fully the position of a head and a scan plane, including when the head is tilted in the scan plane.

Other objects of the invention include providing a way or means for comparing directly scans taken by the same or different imaging modalities and providing a method for the

reproducible placement of external markers, e.g., electrodes, on a patient.

### 3. Summary of the Invention

5       The invention thus provides devices and methods for the non-invasive, imaging or radiographic examination of a subject. By "imaging" is meant any scanning or spectroscopic technique that provides information that can be recorded on a tangible medium (e.g., photographic film, slides and the like) or  
10       electronically for storage, later retrieval, or manipulation. Moreover, the scanning or spectroscopic technique may also give rise to an image that is viewable, e.g., on a screen or monitor. The immediate objective, of course, is to provide information regarding, or an image of, the internal organs or  
15       tissues of a subject. Such scanning or spectroscopic technique or imager can use a wide variety of electromagnetic radiation (or for that matter any suitable source of energy) to probe or excite internal atoms, ions, molecules, structures, cells, tissues, or organs, including but not limited to radio waves,  
20       infrared, ultrasound, ultraviolet, X-rays, electron beam, alpha-, beta-, or gamma-rays or particle emissions.

      Accordingly, the invention provides a stereotactic device that is intended for use with an imager and generally comprises a frame equipped with localizing means and affixing means. The  
25       localizing means comprises one or more localizing arrays that provide one or more imager detectable signals, while the affixing means comprises non-invasive fittings for placement about the periphery of the subject and which permit the reproducible positioning of the frame on the subject.

30       From the signals is derived a personal coordinate system that serves as a reference coordinate system for imaging scans taken of a subject on which the frame is positioned. This personal coordinate system is independent of any machine coordinate system. (Contrast the device of Laitinen et al., for example,  
35       which must be attached to the imaging table or couch to "fix"



the device's (and consequently the patient's) coordinate system to that of the machine coordinate system.) In a specific embodiment of the invention, the localizing means comprises localizing arrays or individual reference elements.

- 5 Alternatively, the localizing array may be made up of one or more reference elements. The resulting three-dimensional reference coordinate system is specific or "personal" to the subject and is independent of the machine coordinate system.

The device, as described further below, may be  
10 reproducibly positioned to the subject without the need for an invasive affixing means, such as staples, pins and/or bolts (i.e., the device of the invention is "non-invasive"; non-invasive can also mean the absence of a surgical intervention or of a breach of a subject's body).

- 15 The invention also relates to method of obtaining imaging scans of a subject which includes providing a non-invasive stereotactic device that is positioned reproducibly on a subject and which device establishes a personal coordinate system (PCS) associated with the subject. Again, the PCS is  
20 independent of a machine coordinate system (MCS) associated with an imager.

Subsequently, using an imager having an MCS, an imaging scan of the subject is taken (including the stereotactic device) to establish the PCS of the subject. The MCS of the  
25 imager is then manipulated to bring the MCS in substantial alignment with the PCS of the subject. One or more additional imaging scans of the subject are taken next, with the MCS of the imager substantially aligned with the PCS of the subject, to provide a first set of imaging scans.

- 30 In yet another aspect of the invention, a method of obtaining imaging scans of a subject taken over different time periods is disclosed. The method comprises taking at a first time period, using an imager, a baseline imaging scan that is relatable to a personal coordinate system (PCS) and a first  
35 machine coordinate system (MCS). The PCS, by definition, can

be regenerated from the subject in a substantially reproducible manner independent of the imager's (or machine's) coordinate system. At a different time period, using a second imager, at least one follow-up imaging scan is taken, which scan is  
5 relatable to the PCS and a second MCS. The second MCS is then manipulated, such that the relationship between the second MCS and the PCS is substantially the same as the relationship between the first MCS and the PCS. At least one additional follow-up imaging scan is then taken, which imaging scan can be  
10 superimposed on the baseline imaging scan. The second imager may be the same as or different from the initial "baseline" imager. It should be understood that follow-up scans can be taken over a wide range of time periods, from very short, essentially back-to-back scans to much longer time periods of  
15 days, to weeks, to years.

A further method of the invention relates to yet another method of obtaining imaging scans of a subject. The method comprises providing a subject with a non-invasive stereotactic device that is positioned reproducibly on a subject. The  
20 stereotactic device, when positioned on the subject, establishes a personal coordinate system (PCS) associated with the subject which, as always, is independent of a machine coordinate system (MSC) associated with an imager. The method continues with a step of taking, using a first imager having a  
25 first MCS, at least one imaging scan of the subject including the stereotactic device to establish the PCS of the subject and to relate the PCS of the subject to the first MCS of the first imager. The next step involves taking, using a second imager having a second MCS, at least one imaging scan of the subject  
30 including the stereotactic device to reestablish the PCS of the subject and to relate the PCS of the subject to the second MCS of the second imager. The second MCS is then manipulated, such that the PCS is related to the second MCS in substantially the same way as the PCS is related to the first MCS. The method  
35 may further comprise taking one or more additional imaging

scans of the subject with the second MCS of the second imager so manipulated.

In this manner, the invention provides a device and methods by which temporally different imaging scans from the  
5 same or different imaging modalities can be compared directly.

The device and methods of the invention thereby satisfy a long felt need in the art by providing a way to define or obtain a personal coordinate system that is independent of the machine coordinate system, the time at which the imaging scans  
10 are taken, the operator of the imager, the brand name of the imager, the model of the imager, or even the modality of the imager.

An exemplary stereotactic device and method of the present invention can thereby facilitate routine examinations of a  
15 patient or subject. In particular, the subject's head can be easily and repeatedly examined with the confidence that imaging scans taken at different time periods can be superimposed or compared directly. In some cases, portions of the patient's spine can also be viewed routinely, e.g., during regular, pre-  
20 and post-surgical planning examinations. The imaging modalities that can be used to advantage (or used with each other in any combination, except that the imaging modality that has a "fixed" - not adjustable -- machine coordinate system should preferably be used to obtain the first, baseline, or initial  
25 set of imaging scans) include MR, CT, PET, SPECT, MEG, and other such imaging/radiologic scanning or spectroscopic techniques.

These and other aspects of the invention are evident from the discussion above and from the more detailed descriptions  
30 that follow of the preferred embodiments of the invention.

#### 4. Brief Description of the Drawings

A better understanding of the invention may be attained by reference to the drawings, provided herein, in which:

Figure 1A depicts a front view of one embodiment of a non-invasive, stereotactic device according to the invention;

Figure 1B depicts a top view of one embodiment of a non-invasive, stereotactic device according to the invention;

5 Figure 1C depicts a side view of one embodiment of a non-invasive, stereotactic device according to the invention;

Figure 2 illustrates a technique for determining the exact position of reference elements based on a pattern of "dots" formed in a scan by the device of Figures 1A, 1B and 1C;

10 Figure 3 illustrates another technique for determining the position of reference elements based on a pattern of "dots" formed in a scan by the device of Figures 1A, 1B and 1C;

Figure 4A depicts a scan of a volunteer's head on which is placed the device of Figures 1A, 1B and 1C, while Figure 4B depicts a modified scan rotated and translated according to a methodology of the invention.

Figure 5 is a flow chart showing a diagnostic procedure according to the invention for determining the orientation of a patient's head.

20 Figures 6A depicts a scan of volunteer's head on which is placed the device of Figures 1A, 1B and 1C, while Figure 6B depicts another scan of the same volunteer, but by a different operator, demonstrating the reproducibility of the inventive method.

25 Figure 7 depicts a volunteer wearing the device of Figures 1A, 1B and 1C.

Figures 8A-8F depict the specifications for one embodiment of the device of the invention.

30 5. Detailed Description of the Invention

The illustrative device and method permit the alignment of routine scans to a pre-defined personal coordinate system. Once this alignment is performed, the location, orientation and size of, e.g., lesions can be reproducibly and precisely  
35 determined. It thus becomes possible to compare locations and

size from different examinations at different times and sites using different machines for a given modality. It is further possible using the stereotactic device of the invention to provide for imaging scans that can be aligned directly and  
5 compared across different imaging modalities.

To accomplish further the objectives of the present invention, the following detailed description is provided which is directed to the lightweight frame, including non-invasive affixing means, localizing means and reference elements for  
10 defining a personal coordinate system and a computational procedure for the manipulation and/or alignment of coordinate systems to permit imaging scans to be taken at different time periods which are superimposable or directly comparable.

15       5.1. Lightweight Frame

In a particular embodiment of the invention, a stereotactic device comprises a lightweight frame having affixing means comprising non-invasive fittings for placement about the periphery of the subject and which permit the  
20 reproducible positioning of the frame on the subject. The non-invasive fittings may include, for example, ear fittings and a nose fitting. The frame is adapted to fit partially or completely around the human head. When present, the nose fitting may rest on the nasion or on or about the bridge of the  
25 nose. Also when included, the ear fittings (usually a pair) may be inserted into the ears or allowed to rest over them (e.g., in substantially the same manner as eye glass frames rest on the bridge of the wearer's nose and over the wearer's ears).

30       Moreover, localizing means, described further below, are preferably conveniently positioned in the proximity of the nose and ear fittings (e.g., one by the nasion and one for each ear fittings for a total of three localizing means). In this way, a cross-sectional imaging scan using an MR, CT, PET, SPECT,

MEG, and/or such other imager can cut across all three localizing arrays of the localizing means in a single slice.

The frame may be equipped with additional, optional features, such as a securing means that facilitates the further  
5 holding or securing of the frame to the subject, especially the subject's head. Such securing means include, but are not limited to, elastic or inelastic components, e.g., fabrics, VELCRO bands and spring assemblies. Preferably, such optional  
10 securing components are integrated with the aforementioned ear fittings. Alternatively, these components may be integral with or detachable from the frame.

Figures 1A - 1C depict front, top and side views of an illustrative stereotactic device according to one embodiment of the invention. The stereotactic device comprises a curved  
15 frame 10 which is worn by the subject in a manner somewhat similar to eyeglass frames. The stereotactic device further comprises affixing means, including a nose fitting 12 fixed to the midpoint of the frame and a pair of ear fittings 14. In some embodiments, the ear fittings are adjustable, slidably  
20 mounted along the frame to accommodate the configuration of the subject's head. The nose fitting is preferably placed on the nasion, and the ear fittings are preferably placed in, on, or over the ears, more preferably in the outermost portion of the external auditory canals.

25 Referring again to Figure 1A, the frame 10 can be of variable length, preferably, a length of approximately 15 inches or so, and is formed into a shape providing for comfortable use on a typical human adult. Such a shape may be, e.g., a slight curve, a half circle, a "U," or the like.  
30 Different sizes can also be made to accommodate smaller-sized heads, such as an adolescent's or child's head.

Preferably, the materials used for making the frame are low-cost, non-magnetic and transparent to the imaging system. Moreover, the materials should be durable and preferably  
35 amenable to repeated sterilization (especially when

implementing non-disposable frames). Preferred materials for the frames include relatively rigid thermoplastic materials, including most synthetic polymers but most preferably plexiglass.

5

#### 5.2. Localizing Means

In this aspect of the device, the frame is equipped with localizing means comprising one or more, preferably at least three, of what are referred to herein as localizing  
10 arrays. Each array provides one or more imager detectable signals from which the personal coordinate system of the subject is derived. With the personal coordinate system serving as the reference coordinate system for the initial, baseline imaging scans and each subsequent follow-up imaging  
15 scans, the stereotactic examination of the subject is facilitated.

In a particular embodiment of the invention, the localizing array is made up of one or more reference elements, preferably including a pair of reference elements. A suitable  
20 reference element may comprise an elongate component, e.g., a cylindrical rod or tube. Other localizing means and corresponding localizing arrays would be apparent to one of ordinary skill on appreciation of the disclosure provided herein. For example, a localizing array may comprise a  
25 supporting means, such as a cylindrical guide directed toward the body of the subject, into which a digitizing "pen" can be inserted. The digitizer can, in turn, emit signals that can be observed and/or recorded on an imaging scan. Also, depending on the number of localizing arrays, which are provided with a  
30 frame, the reference elements can include spherically shaped, egg-shaped, or irregularly shaped "opaque" (more, below) materials to create points in space.

The preferred elongated pair of reference elements can have a number of configurations but are preferably arranged in  
35 a spaced-apart "X" configuration. In one embodiment of the

invention, the elongate components of each pair form an "X" but do not intersect. Rather, the elongate components (e.g., rods or tubes) are staggered from one another so as to be spaced apart. Thus, e.g., the reference elements of an array, positioned in the proximity of, or at, the nasion, inscribe an "X" configuration when viewed initially from the front of the head and form spaced apart, substantially parallel lines when viewed from the top of the head at approximately a ninety degree angle from the initial view. Generally, the reference elements can be spaced apart by any practical distance, but preferably range from about 0.1 to about 1 inch, more preferably, about 0.2 to about 0.5 inch.

The reference elements are constructed or filled with materials that produce distinctive features in an imaging scan, such as a radiographic scan using an MR imager or CT scanner. For example, the reference elements can be filled with doped water, which is relatively "opaque" (i.e., give rise to detectable signals in the course of the imaging scan) to MR, or they can be constructed of a material that is itself opaque to MR (e.g., stainless steel). When such a stereotactic device is worn on, e.g., the head of, a patient being scanned, the reference elements appear as "dots" (in the case of cylindrical, rod-like, or spherical components) or other distinctive features (in the case of non-cylindrical or irregularly shaped components) in the resulting scan.

Referring again to Figures 1A, 1B and 1C, a localizing means is shown comprising three localizing arrays, each array in turn comprising paired reference elements 16A/16B, 18A/18B and 20A/20B. The three localizing arrays are each mounted on three ear and nose fittings, as shown. Each pair of reference elements is arranged in the form of an "X," when viewed from the front (tubes 16A/16B) or side (tubes 18A/18B and 20A/20B) and is constructed from, or preferably filled with, a radiographically detectable substance, such as doped water.



In cross-sectional, radiological scans, such as MR images, the paired reference element tubes appear as two dots at each fitting or location, six dots in toto. Those dots are shown in Figures 4A and 4B, where dots a and b correspond to the cross-sectional image of the paired reference elements 16A/16B, respectively; dots c and d correspond to the image of the paired reference elements 20A/20B; and dots e and f correspond to the image of the paired reference elements 18A/18B.

As stated above, the reference elements may be made of a variety of materials or combinations thereof, including plexiglass or other non-magnetic, radio-transparent material that is filled with a radio-opaque substance. Alternatively, these elements may be formed from a radio-opaque substance, such as steel or other metal. The reference elements can be circular in cross-section (e.g., with a radius of approximately 0.05 to approximately 0.4 inch, preferably about 0.2 inch, more preferably about 0.1 inch) or of any other cross-sectional shape readily discernible on a scan. Where the reference elements are in the form of cylindrical tubes, they are generally from about one to about five inches in length, preferably about two inches in length.

In one embodiment of the invention, in which the reference elements are paired, the members of each pair are generally spaced apart from one another. This spacing may be about 0.1 to about 0.5 inch but is most preferably about 0.2 inch.

The reference elements are mounted on plexiglass or other non-magnetic, radio-transparent support of any size suitable for providing a supporting surface for the tubes without making the stereotactic device unwieldy. For example, squares of approximately one-by-one inch to five-by-five inches, preferably about two-by-two inches, more preferably about 1.4 x 1.4 inches, are suitable for use as the support for the reference elements. Hence, in a particular embodiment of the invention, the combination of support and the reference elements comprise a localizing array. In another embodiment of

the invention, a support may also serve as a guide for a digitizing "pen" that can be manipulated by a physician or technician and which generates detectable signals at locations that can be observed and pinpointed in an imaging scan. In  
5 still other embodiments of the invention, supports may be dispensed with and the reference elements are found directly on or in the frame (e.g., the elements may be an integral part of the frame).

As used herein the term "radio-opaque" and  
10 "radiographically opaque" refer to materials, such as doped water, which are visible on an MRI scan or on such other radiologic scan. Of course, a generally "opaque" material can be chosen so that detectable signals can be observed in each, or some, of MR, PET, SPECT, CT, MEG, or X-ray, as the case may  
15 be, and using which material portions of the stereotactic device (e.g., the reference elements) according to the invention are made. Likewise, the term "radio-transparent" refers to materials, such as plexiglass, plastics and most synthetic polymer materials, which are generally not visible on  
20 an MRI scan or on such other radiologic scan (e.g., PET or SPECT), with which portions of the stereotactic device (e.g., the frame) according to the invention is used. Such radio transparent materials can also be used in combination with radio opaque materials, as would be apparent to one of ordinary  
25 skill. It should be noted that plexiglass, plastics and most synthetic polymers are visible, and thus opaque, in certain imaging modalities, such as CT or X-ray.

### 5.3. Imaging Procedure

30 To analyze a scan that includes an image of the reference element tubes, a reference point is first defined; most suitably, the cross-point of each pair of reference element tubes in the above-described "X" configuration can serve as this reference point. Assuming the image is in the  
35 in-scan plane, e.g. as in Figures 4A and 4B, the x and y

coordinates of the reference point can be found as the mid-point between two dots on the image. The z coordinate, or the through-plane position, is determined from the distance of the two "dots" generated by each tube. As a result, the three-dimensional positions of three reference points (one from each pair of tubes) with respect to the MCS are obtained from a single axial image. These reference points, in turn, define the personal coordinate system.

The machine coordinates (i.e., the machine coordinate system) can then be adjusted to rotate and translate the scan to a predetermined plane defined by the personal coordinate system. In this manner, the machine coordinates system can always be made to coincide with reference points that are independent of the machine and which are determined in relation to the specific patient or subject. Hence, a series of imaging scans can be obtained of the same patient at different times, independent of the operator or the specific imaging instrument, all of which are substantially superimposable on one another, including the initial set or baseline set of imaging scans. Also, images from differing imaging modalities can be "merged" by using the stereotactic devices and methods of the invention to provide a composite image comprising superimposed images taken from one or more different imaging modalities.

More particularly, analysis of an imaging scan to determine the position of the reference elements of the aforementioned stereotactic device can be accomplished by the methods of the invention, such as those described in detail, below.

#### 5.3.1. Two-Scan Exact Positioning Method

From two or more imaging slices that cut through both tubes of each of the three localizing arrays, the exact location of the reference point can be calculated mathematically as follows.

Referring again to Figure 2, points a, b, c and d are where the two planes of the two imaging slices cut through the

staggered "X" (thin lines). The x, y and z coordinates in the initial imaging coordinate system can be read from the images. In addition, e and f are points on the tubes where the two tubes are closest to each other, and the reference point, g, can be defined as the mid-point between e and f. The objective is to find the coordinates of g, given coordinates of a, b, c and d.

Two unit vectors, parallel to each of the tubes,  $V_1$  and  $V_3$ , can be defined as:

10

$$V_1 = \frac{b-a}{|b-a|}$$

15

$$V_3 = \frac{d-c}{|d-c|}$$

20

Also, a third vector which is orthogonal to  $v_1$  and  $v_3$  can be defined as:

25

$$V_2 = V_1 \times V_3$$

where  $\times$  denotes the vector (outer or cross) product.

Then line segments a-e-f-d can be expressed as:

30

$$AV_1 + BV_2 + CV_3$$

where A, B and C are (scalar) distances between a and e, e and f, and f and d, respectively.

Since the vector a->e + e->f + f->d is also equal to a->d, then  $V_4$  can be defined as:

35

$$V_4 = d - a$$

and

$$V_4 = [V_1 V_2 V_3] \begin{bmatrix} A \\ B \\ C \end{bmatrix}$$

Since  $V_1$ ,  $V_2$  and  $V_3$  are orthogonal,  $A$ ,  $B$  and  $C$  can be obtained as:

$$\begin{bmatrix} A \\ B \\ C \end{bmatrix} = [V_1 V_2 V_3]^{-1} V_4 = [V_1 V_2 V_3]^T V_4$$

where "T" is transpose.

The point  $g$  is:

$$g = a + AV_1 + \frac{B}{2} V_2$$

For the above-described computational method to work well, the relative position of the two reference element tubes in each localizing array must be defined by some known, non-zero angle. The above steps are simplified by assuming that the two tubes in each localizing array are orthogonal to each other. However, the above-described method also works as long as two tubes have any pre-determined, non-zero angle. In that case, however, the inversion of  $[V_1 V_2 V_3]$  becomes necessary, as will be apparent to one skilled in the art.

It is further preferable for the sake of simplicity in calculating the scan position to have the angles between the tubes in each localizing array to be the same. Again, however, this is not critical under the practice of the invention so long as the angles of the tubes in each localizing array are known.

### 5.3.2. Single-Scan Positioning Method

It is also possible to determine the position of the reference point from a single slice relatively accurately, although mathematically not exact. Assuming the imaging scan is in the x-y plane, the x and y coordinates of the reference point can be found as the mid-point between two dots on the image. The z coordinate, or the through-plane position, can be determined from the distance between the two dots. Since the two tubes are arranged in a staggered "X" configuration, the direction in the z axis can be determined knowing the angle between the elongated components. As a result, the positions of three reference points in all three dimensions are obtained from a single axial image.

Referring now to Figure 3, points a and b are where the imaging plane (thin line) cut through the staggered "X" (thick lines). The distance D is defined as the distance between the points a and b on the image and corresponds to the distance between the two tubes that make up the "X" of the localizing array. The x and y coordinates of the reference point, m, can be found on the image as the midpoint between the dots. The z coordinate of the reference point, z, can be calculated as:

$$z = \sqrt{\left(\frac{D}{2}\right)^2 - \left(\frac{d}{2}\right)^2}$$

### 5.3.3. Computational Method

The detailed calculation method for determining the orientation of a patient's head is as follows:

Let p1, p2 and p3 be vectors representing three reference points in the initial image coordinate system corresponding to a/b, c/d and e/f in Fig. 4A, respectively. These points are calculated as described above. Then, unit vectors representing the new, desired personal coordinate system, x, y, z, can be calculated as:

$$\begin{aligned}
 x &= p3 - p2 \\
 z &= x \times (p1 - p2) \\
 y &= x \times z
 \end{aligned}$$

5 where  $\times$  denotes the vector product operation. A rotation matrix that rotates these into xyz axes is obtained as:

$$10 \quad R = \begin{bmatrix} x^T \\ y^T \\ z^T \end{bmatrix}$$

15 where "T" is transpose and the translation vector  $t$ , is

$$t = -R \frac{p2 + p3}{2}$$

20 A general diagnostic method according to the invention is outlined in Figure 5, including determining a standard reference coordinate system that is based on the personal coordinate system. First, a stereotactic device, as described above, is placed on the patient. Next, the patient is placed  
25 in the imaging device while wearing the stereotactic device. The patient position is adjusted so that an axial image cuts across all tubes in at least three localizing arrays. A scan is taken subsequently. An exemplary resulting scan is shown in Figure 4A.

30 From such a scan, the three patient reference points of the personal coordinate system are calculated as described above. From these points, a rotation matrix and a translation vector are calculated to adjust the initial imaging coordinate system to the personal coordinate system, as defined by the  
35 stereotactic device. On the MR imager, these transformations are applied to the gradient fields, receiver frequency and phase to change the machine coordinate system.

Next, another axial imaging scan is obtained in the new standard reference coordinate system and the "dots" are checked  
40 to ensure that the "dots" are aligned at the predetermined

positions. The scan of Figure 4A, modified in accord with this method of the invention, is shown in Figure 4B.

Once a standard reference coordinate system is determined by the foregoing steps, then a full set of examinations is  
5 obtained using the defined rotation matrix and the translation vector. The entire image alignment process can be performed in a minimal time as compared to previously known scanning techniques in which an attempt is made to adjust or fix the patient coordinate system each time relative to the coordinate  
10 system of the imager.

#### 5.4. Additional Supporting Disclosure

A still further aspect of the invention provides a stereotactic device for non-invasive stereotactic examination,  
15 particularly of the head of a subject, comprising a frame that is reproducibly positioned on the subject. The frame may have any number of localizing means comprising radio-opaque reference elements to provide for a multi-dimensional reference coordinate system. In a preferred embodiment, six reference  
20 elements are included, which are arranged in pairs to provide three localizing arrays.

The frame of the stereotactic device is preferably made of a non-radiographic material, preferably plexiglass. Other suitable radio-transparent materials include, but are not  
25 limited to plastics, synthetic polymers, or other carbon-based materials of some structural rigidity, such as poster board, cardboard, or even graphite.

In a particular embodiment, the frame provides a three-dimensional framework for the at least four reference elements  
30 to provide a three-dimensional personal coordinate system. In such an embodiment, the localizing means comprises four or more localizing arrays each comprising a reference element. Each reference element, in turn, defines a point in space, three of which points define a unique plane and the fourth point lying  
35 outside the unique plane.



In yet another embodiment three reference elements can be designed into the device to provide inherently the fourth reference element necessary to define a three-dimensional space (e.g., as described earlier, confining two of the three reference elements to a pre-determined plane).

The reference elements are positioned on the frame at predetermined positions to provide the three dimensional coordinate system. As described above, the reference elements can be paired in an orthogonal arrangement and be constructed or filled with materials that produce "dots" or other distinctive features in an imaging scan plane. These elements make up the localizing means that provides a reproducible localization of the multi-dimensional personal coordinate system. Thus, the reference elements may include markings such as small paint spots, indentations, slots, grooves, and the like, in or on the frame whose positions can be entered into or recorded in a scan via, e.g., an MRI-compatible digitizer.

Hence, in a preferred embodiment of the invention a stereotactic device for use with an imager comprises a frame equipped with localizing means and affixing means. The localizing means comprises three or more localizing arrays each equipped with two or more reference elements that together provide six or more imager detectable signals. The affixing means comprising three or more non-invasive fittings for placement on the subject's nasion and in or about the subject's ears. The fittings, together, permit the reproducible positioning of the frame on the subject and the reference elements each provide an imager detectable signal. The personal coordinate system is then derived from these signals, collectively.

The reference elements preferably comprise elongate components. For example, two elongate components are arranged in an "X" configuration and are related to one another by a predetermined angle, e.g., about 90 degrees. Further, the reference elements comprise radiographically opaque or semi-

opaque material, including steel or doped water. The signals obtained from the reference elements are preferably detectable by MR, CT, PET, SPECT, EEG, or MEG. In an alternative embodiment, the imager detectable signals are provided by a digitizer used in conjunction with the one or more localizing arrays.

The preferred device may further comprise a securing means that facilitates the securing of the frame to the subject. Such securing means may include an inelastic or elastic component.

In use, the stereotactic device is reproducibly positioned on the head of a subject. The position of the reference elements with respect to the desired location of the subject is then digitally recorded, e.g., with an MRI-compatible digitizer. The digitized positions of the reference elements provides a reproducible personal coordinate system. Subsequently, the positional rotation and translation necessary to bring the machine coordinate system into alignment with the personal coordinate system can be determined, preferably by a digital processor. After the machine coordinate system is adjusted to align with the personal coordinate system, one or more radiographic scans are taken.

In subsequent scans, the patient again reproducibly dons the stereotactic device and the positions of the reference elements are digitally recorded. The second imager is then adjusted to the personal coordinate system by means of a translation and/or rotation of the second imager's machine coordinate system, as above. The second and subsequent scans are then taken, again in the patient coordinate system. By scanning each time in the patient coordinate reference system, all scans can be directly compared.

Described above are improved devices and procedures for non-invasive, radiographic analysis, particularly stereotactic head examinations, e.g., in connection with stereotaxy or other similar surgical procedures, meeting the objects of the

invention. Some of the more noteworthy features of the invention include, but are not limited to:

1. A stereotactic device that can be made with extremely low cost and which can be made in disposable or re-usable form;
- 5 2. A method of aligning the imaging plane in which only one axial image through the device is necessary to perform the subsequent alignment; the only human intervention required is the identification of the reference points ("dots") of the personal coordinate system on the localizing axial image; the  
10 rest of the process can be implemented in the imagery and processed automatically; moreover, with an automated mechanism to identify the "dots," the entire process can be fully automated;
3. Imaging scans acquired according to the invention are  
15 alignable to a reproducible reference coordinate system, so that the images from different examinations can be compared directly; these examinations could be performed at different institutions, with different imagers, etc., as long as all examinations are taken with a device of the invention  
20 positioned on the subject;
4. A device and method best used in obtaining MR images; however, other imaging modalities, such as CT, PET, SPECT, or MEG, are also applicable; these other imaging modalities can then be cross-referenced with MR imaging scans.
- 25 The stereotactic device of the invention is exemplified as an eyeglass-like structure. However, the invention may be of any suitable structure that can support the localizing arrays or reference elements and which can be reproducibly positioned on the subject. Hence, the invention provides a way  
30 of mapping an anatomical region of a subject which can be related to a personal coordinate system that is independent of the machine coordinate system. Furthermore, the device and methods of the invention may also be amenable to veterinary applications.

It should thus be apparent that the present invention provides a method of obtaining imaging scans of a subject comprising the steps of: providing a subject with a non-invasive stereotactic device that is positioned reproducibly on the subject and which establishes a personal coordinate system (PCS). The PCS is associated with the subject independent of a machine coordinate system (MCS) that is associated with an imager; taking, using an imager having an MCS, an imaging scan of the subject including the stereotactic device to establish the PCS of the subject; manipulating the MCS of the imager to bring the MCS in substantial alignment with the PCS of the subject; and taking one or more additional imaging scans of the subject with the MCS of the imager substantially aligned with the PCS of the subject, to obtain a first set of imaging scans.

The method of the invention may further comprise repeating the above-mentioned steps at a second time period, using a second imager, to obtain a second set of imaging scans. Subsequently, at least one imaging scan of the first set can be compared with at least one imaging scan of the second set. In this way, an operator has the opportunity to note and make a record of any previously undetected anatomical feature of the subject. Moreover, observations can be made of any changes in any previously detected anatomical feature of the subject. As mentioned above, such anatomical features may be of anything that can be of interest to the subject or the medical practitioner, including but not limited to lesions, tumors, or features that may indicate a pathological condition. Adventitiously, the stereotactic device is positioned reproducibly on the subject's head.

The second time period of the disclosed method represents an elapsed time from the taking of the first set of imaging scans to the taking of the second set of imaging scans. This elapsed time may, of course, be any time period appropriate to the examination process, including periods that are very short (e.g., essentially back-to-back scans), intermediate (e.g.,

days to weeks), or very long (e.g., years). For instance, the elapsed time period may be about 15 to about 45 minutes, a few hours, one day to about one week, about one week to about one month, about one month to about six months and about six months to about one year. This second time period may even represent an elapsed time from the taking of the first set of imaging scans to the taking of the second set of imaging scans of about one year to about five years.

Separately, the invention provides a method of obtaining imaging scans of a subject comprising the steps of (a) providing a subject with a non-invasive stereotactic device that is positioned reproducibly on a subject and which establishes a personal coordinate system (PCS) associated with the subject which is independent of a machine coordinate system (MCS) associated with an imager; (b) taking, using a first imager having a first MCS, at least one imaging scan of the subject including the stereotactic device to establish the PCS of the subject and to relate the PCS of the subject to the first MCS of the first imager; (c) taking, using a second imager having a second MCS, at least one imaging scan of the subject including the stereotactic device to reestablish the PCS of the subject and to relate the PCS of the subject to the second MCS of the second imager; and (d) manipulating the second MCS, such that the PCS is related to the second MCS in substantially the same way as the PCS is related to the first MCS.

In this method of the invention, the second MCS is substantially aligned with the first MCS. In a specific embodiment, the first imager may be an imager in which the machine coordinate system cannot be adjusted to the personal coordinate system (i.e., the machine coordinate system is fixed, as with a CT scanner). If so, the second imager is one whose machine coordinate system is adjustable, preferably, an MR imager. The method involving different imaging modalities may further comprise forming a composite image including

information from at least one imaging scan taken using the first imager and information from at least one imaging scan taken using the second imager.

In addition, the present invention also relates to a method of spatially aligning at least two radiographic imaging scans of the head of a subject taken by a radiographic scanning device comprising: (a) radiographically scanning the head of a subject wearing a stereotactic device of the invention to provide a first radiographic imaging scan containing a plurality of reference points defining a first personal coordinate system; (b) relating the first personal coordinate system with a personal coordinate system obtained from a prior radiographic imaging scan of the subject reproducibly wearing the stereotactic device; (c) adjusting the radiographic scanning device to align the first and prior personal coordinate systems; and (d) obtaining one or more additional radiographic imaging scans of the subject with the radiographic scanning device so adjusted.

The following additional examples are provided to further illustrate preferred aspects of the invention. Nothing in these additional examples should be construed to limit the invention in any way.

## 6. Examples

### 6.1. General Method

In a generic embodiment of the invention, a pulse sequence to rotate the imaging coordinate system is executed on a clinical MR imager (e.g., a 1.5T Signa, GE Medical Systems). The rotation matrix is determined by a conventional digital data processor (e.g., a personal computer) programmed to calculate the rotation matrix from the positions of the reference points of the frame. A listing of the relevant computer programs are attached hereto, as Appendices A and B.

Those skilled in the art will appreciate that rotation of the imaging coordinate system and determination of the rotation matrix can be implemented on the image as a single step. In that case, the necessary operation is reduced to identifying  
5 the positions of the reference points (e.g., 6 points in a specific embodiment) on the first image. Hence, the required sophistication of the technologist is greatly reduced by the inventive method.

10        6.2. Use of an MRI-Compatible Digitizer

In a specific embodiment of the invention, the reference points in the first scan are entered into a digital data processor by means of an MRI-compatible digitizer. In this embodiment, the technologist need only mark the position  
15 of the reference elements on the first scan and the digital data processor calculates the patient-defined personal coordinate system from the digitized entries using, e.g., the computational examples given above.

20        6.3. Use of Electrodes for Determining Brain Structures

In yet a further embodiment of the invention, the correlation of electrical activity in the brain with specific  
25 brain structures may be reproducibly accomplished. In this embodiment, an MR imaging scan is taken of the patient wearing the stereotactic device to obtain a "baseline" scan. (It should be noted that as long as the device of the invention is  
30 worn, the baseline scan may be taken before or after the EEG.)

An EEG is then taken of the patient, with the device in place. One or more electrodes, typically 15-30 electrodes, are then positioned on the head of the patient. The position of each of the electrodes is then entered into a digital signal  
35 processor, e.g., as described above, to define the electrode

positions with respect to the patient coordinate system as defined by the device.

If any aberrant, unusual, or abnormal traces are observed from the EEG, the identity and position of the electrode or electrodes giving rise to such traces can be determined. The MR imager is subsequently utilized to provide an imaging scan across the positions of the electrodes of interest. One or more scans are taken to obtain images of the patient's anatomy, which may give rise to the aberrant traces. Through this alignment technique, electrical signals detected by the electrodes can be correlated with particular brain structures to a high degree of accuracy and reproducibility.

#### 6.4. Follow-Up Electroencephalography (EEG)

The general positions of each electrode can be reproduced, if desired, to correspond with an initial EEG, using the device of the invention. Alternatively, each new configuration of the electrodes can be recorded digitally relative to the PCS established by the device, and MR images can be taken selectively based thereon.

When seeking a reproducible placement of electrodes for use in electroencephalography (EEG), a series of MR imaging scans is taken of a patient wearing the stereotactic device of the invention, as described above, to establish the personal coordinate system. One or more electrodes are then placed on the patient's head, and the position of the electrodes is digitized, as described above. The location of the electrodes is thereby determined and recorded relative to the personal coordinate system.

Upon subsequent EEG examinations, the patient wears the stereotactic device of the invention. One or more scans are taken to reestablish the personal coordinate system. One or more electrodes are again placed on the patient so that their positions correspond to their original positions in the initial EEG/MRI scan. Correct placement of the electrodes is checked



by comparing the prior scan and electrode placement with that of the subsequent scan.

Accordingly, any changes in the electrical activity of the patient can be attributed to specific electrodes and/or patient anatomical features as revealed by the MRI.

#### 6.5. Imaging Across Different Modalities

A further aspect of the invention provides for the direct comparison of imaging scans taken with different modalities, particularly wherein at least one of the modalities has a coordinate system that is not adjustable. In this embodiment, e.g., a first scan having fixed machine coordinates is taken of the subject wearing the stereotactic device of the invention. The reference elements are located in the scan and a personal coordinate system is established therefrom. Additionally calculated is the translation and rotation of the machine coordinate system required to align the machine with the personal coordinate system.

A second scan is later taken with a modality in which the machine coordinate system can be adjusted (e.g., MR imager) with the patient reproducibly wearing the stereotactic device. The reference elements are identified in the second scan and the personal coordinate system determined. The value of the difference in the personal coordinate system and the machine coordinate systems for the initial and second scans are determined.

With the common personal coordinate system in place, the second imager is then adjusted to translate and/or rotate the second imager coordinate system so that the difference between the second image coordinate system and the second personal coordinate system coincides with the difference between the first image coordinate system and the first personal coordinate system.

Subsequent scans are then taken with the second imager aligned with the scan plane of the first imager, permitting a

highly reproducible direct alignment of scans taken in the two different modalities based upon the common personal coordinate system.

The stereotactic device and procedure of the invention can thus be used to align images from modalities such as computed tomography (CT), positron emission tomography (PET), single photon emission computed tomography (SPECT), electroencephalography (EEG) or magnetoencephalography (MEG), and the like.

10 In the case of CT and the device of the invention, an illustrative procedure is as follows (NB: It is not possible to freely position the CT slice, hence, MR images have to be rotated to the CT plane.):

15 First, the CT examination is done with the device on. The position of the reference points (mid-point of the X-shaped rods) in the CT coordinate system is calculated. Next, an MR axial slice through the device is taken, and the MR coordinate system is rotated/translated to coincide with the CT coordinate system, i.e., the second machine coordinate system is  
20 substantially aligned with the first machine coordinate system. Imaging slices that are of the same location/thickness as those of the CT examination are then taken.

As is readily evident to those skilled in the art, similar procedures can be employed for aligning other imaging  
25 modalities. In this way, all imaging capabilities can be linked through the use of MR under the practice of the invention.

#### 6.6. Process for Determining Subject Head Orientation

30 Still another aspect of the invention provides a method for determining the orientation of a subject's head. The procedure includes placing a plurality of, preferably three, localizing arrays of the "X"-type, described above, about the head of a subject patient, e.g., substantially  
35 adjacent the nasion and ears, or in other locations spaced

apart about the circumference of the head. The procedure further includes taking a cross-sectional imaging scan of the head in the vicinity of the localizing arrays and determining the orientation of the head based on the pattern of "dots" (or  
5 other distinctive features generated by the reference elements) in the imaging scan. This operation may be accomplished conveniently through use of the computer-implemented program appended hereto. Adjustments to the orientation of the subject's head can then be performed as needed or desired.

10

#### 6.7. Further Examples

The stereotactic device and the correction procedure, described above, are used with both phantoms and human volunteers. The standard quadrature head coil is used for  
15 taking the imaging scans.

Figures 4A-4B show a typical set of imaging scans, which is acquired with a volunteer. As noted above, Figure 4A is the initial axial image taken through the device, and Figure 4B is the image taken after the manipulation step, e.g., the rotation  
20 and translation steps, is applied. All three pairs of dots are aligned with each other, indicating the imaging plane is now cutting through the three reference points. Also, the reference points are at the pre-determined locations.

To demonstrate the reproducibility of the method, the  
25 following study is carried out: First, the device is positioned on the volunteer, and the first axial MR slice is taken. Rotation/translation correction is applied and a set of multi-slice images is taken. The volunteer is withdrawn from the magnet. The device is removed, and replaced again on the  
30 subject by a different technologist. Images are taken again in the same manner as in the first scan set.

Several slices from these two examinations are shown in Figures 6A and 6B. Figure 6A shows the images taken by the first operator, and Figure 6B shows the images taken by the  
35 second operator. (Imaging parameters are: modified RARE

sequence, 30 cm FOV, 256 x 256, 3 mm slice, single slice axial scan (Figures 4A and 4B) and multi-slice axial scan with 20 cm FOV (Figures 6A and 6B).)

As is evident from these pictures, a high degree of reproducibility in scan sections is provided by the device and method of the invention.

The accuracy in reproducing slice position and orientation between different time points is evaluated in phantom and human volunteer studies. The error in phantom studies, when using the mathematically exact, two-scan method, is about 1 mm or less! In human volunteer studies, the error is somewhat higher due to patient motion, though still readily acceptable for use in comparison of the sizes and locations of lesions from one exam to another. In particular, the device of the invention allows for routine scanning, in part because of the little time (2 to 3 minutes) required for device positioning, reference scanning and determination of reference points.

Those skilled in the art will appreciate that the embodiments described above are exemplary and that other embodiments incorporating alterations and modifications therein fall within the scope and spirit of the invention. Each of the references mentioned above is incorporated by reference herein.

## Appendix A

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```

5  /*
    calculate rotation matrix for the "frame"
    find the rotate matrix and the translate vector

    2-21-1995 K. Oshio
10  last modified on 8-1-1995 (correction step)

    (localizer : 1 axial plane. target : axial plane)

        <- 0      was : -> 1
15      -> 1      was : <- 2

        2 v ^ 3      4 ^ v 5

20  --- plan ---
    spinor output (for typing convenience)
    */

#include <stdio.h>
25  #include <math.h>

main()
{
    double      x[6], y[6];          /* ref points in ref plane */
30    double      p0[3], p1[3], p2[3], p3[3]; /* ref vectors */
    double      X[3], Y[3], Z[3];    /* axes */
    double      R[3][3];             /* rot matrix */
    int         i;
    char        corr[256];
35    double      thap, thlr;

    /* (1) input 6 points */
    get_point("ref 0 (x y) ? ", &x[0], &y[0]);
    get_point("ref 1 (x y) ? ", &x[1], &y[1]);
40    get_point("ref 2 (x y) ? ", &x[2], &y[2]);
    get_point("ref 3 (x y) ? ", &x[3], &y[3]);
    get_point("ref 4 (x y) ? ", &x[4], &y[4]);
    get_point("ref 5 (x y) ? ", &x[5], &y[5]);

45    /* (2) convert to 3 ref vectors */
    /* x */
    p1[0] = (x[0] + x[1]) / 2;

```

```

    p2[0] = (x[2] + x[3]) / 2;
    p3[0] = (x[4] + x[5]) / 2;
    /* y */
    p1[1] = (y[0] + y[1]) / 2;
5    p2[1] = (y[2] + y[3]) / 2;
    p3[1] = (y[4] + y[5]) / 2;
    /* z */
    dist_to_z(&p1[2], x[0], y[0], x[1], y[1]);
    dist_to_z(&p2[2], y[2], x[2], y[3], x[3]);
10    dist_to_z(&p3[2], y[5], x[5], y[4], x[4]);

    print_vector("p1", p1);
    print_vector("p2", p2);
    print_vector("p3", p3);
15

/* (2.5) correction */
    printf("correction step ? (y/n) ");
    scanf("%s", corr);
    if (corr[0] == 'y') {
20        thap = atan(((p2[2] + p3[2]) / 2 - p1[2])
                     / ((p2[1] + p3[1]) / 2 - p1[1]));
        thlr = atan((p3[2] - p2[2]) / (p3[0] - p2[0]));
        p1[0] -= p1[2] * sin(thlr);
        p1[2] *= cos(thlr) * cos(thap);
25        p2[1] += p2[2] * sin(thap);
        p2[2] *= cos(thlr) * cos(thap);
        p3[1] += p3[2] * sin(thap);
        p3[2] *= cos(thlr) * cos(thap);

30        printf("thap = %f    thlr = %f\n", thap, thlr);
        print_vector("p1", p1);
        print_vector("p2", p2);
        print_vector("p3", p3);
    }
35

/* (3) make 3 axes */
    vsub(X, p3, p2);          /* X */
    vsub(Y, p1, p2);          /* temp */
    vemul(Z, X, Y);           /* Z */
40    vemul(Y, Z, X);          /* Y */
    vnorm(X); vnorm(Y); vnorm(Z);

/* (4) rotate mat */
    for (i = 0; i < 3; i++) {
45        R[0][i] = X[i];
        R[1][i] = Y[i];
        R[2][i] = Z[i];

```

```

    }

    vmmul(X, R, X);
    vmmul(Y, R, Y);
5    vmmul(Z, R, Z);
    vadd(p0, p2, p3);
    vcmul(p0, 0.5, p0);

    /* print result */
10    mtrans(R);          /* inverse */
    vcmul(p0, -1.0, p0); /* inverse */

    /* correction */
    p0[2] = -p0[2];          /* I+, S- */
15    R[0][1] = -R[0][1];
    R[1][0] = -R[1][0];
    R[0][2] = -R[0][2];
    R[2][0] = -R[2][0];

20    printf("\n");
    print_matrix("R : ", R);
    print_vector("p0", p0);
}

25    dist_to_z(z, x1, y1, x2, y2)
    double *z;
    double x1, x2, y1, y2;
    {
        double      d2 = 9;
30    double      r1, r2;
        double      sign;

        r1 = (x1 - x2) / 2.0;
        r2 = (y1 - y2) / 2.0;
35    if (r1 > 0) sign = 1;
        else sign = -1;
        r2 = r1*r1 + r2*r2;
        r2 -= d2;
        if (r2 < 0) r2 = 0;
40    *z = sign * sqrt(r2);
    }

    /* ***** minimal vector math ***** */

45    get_point(prompt, x, y)
    char *prompt;
    double *x, *y;

```

```
{
    printf(prompt);
    scanf("%lf %lf", x, y);
}

5  get_vector(prompt, v)
    char *prompt;
    double *v;
{
10     printf(prompt);
    scanf("%lf %lf %lf", &v[0], &v[1], &v[2]);
}

    print_vector(prompt, v)
15     char *prompt;
    double *v;
{
    printf(prompt);
    printf("[%5.3lf, %5.3lf, %5.3lf]\n", v[0], v[1], v[2]);
20 }

    print_matrix(prompt, m)
    char *prompt;
    double m[][3];
25 {
    int i;

    for (i = 0; i < 3; i++) {
        print_vector(prompt, m[i]);
30     }
}

vadd(c, a, b) /* c = a + b */
    double *c, *a, *b;
35 {
    int i;
    for (i = 0; i < 3; i++) c[i] = a[i] + b[i];
}

40 vsub(c, a, b) /* c = a - b */
    double *c, *a, *b;
{
    int i;
    for (i = 0; i < 3; i++) c[i] = a[i] - b[i];
45 }

vcmul(c, a, b) /* c = a * b */
```



```
double      a;
double      *b, *c;
{
    int      i;
5   for (i = 0; i < 3; i++) c[i] = a * b[i];
}

vimul(c, a, b)      /* c = a * b */
double      *a, *b, *c;
10  {
    int      i;
    *c = 0;
    for (i = 0; i < 3; i++) {
        *c += a[i] * b[i];
15  }
}

vemul(c, a, b)      /* c = a X b */
double      *c, *a, *b;
20  {
    double    tmp1[3];
    double    tmp2[3];
    int      i;

25  for (i = 0; i < 3; i++) {
        tmp1[i] = a[i];
        tmp2[i] = b[i];
    }
    c[0] = tmp1[1] * tmp2[2] - tmp1[2] * tmp2[1];
30  c[1] = tmp1[2] * tmp2[0] - tmp1[0] * tmp2[2];
    c[2] = tmp1[0] * tmp2[1] - tmp1[1] * tmp2[0];
}

vnorm(a)
35  double    a[3];
{
    double    r;
    int      i;

40  r = 0;
    for (i = 0; i < 3; i++) {
        r += a[i] * a[i];
    }
    r = sqrt(r);
45  for (i = 0; i < 3; i++) {
        a[i] /= r;
    }
}
```

```

    }

    vmmul(c, a, b)      /* c = Ab */
        double          *c, a[3], *b;

5      {
        int    i;
        double    tmp[3];
        for (i = 0; i < 3; i++) tmp[i] = b[i];
        vimul(&c[0], a[0], tmp);
10      vimul(&c[1], a[1], tmp);
        vimul(&c[2], a[2], tmp);
    }

15  mmul(c, a, b)      /* C = AB */
        double          c[3], a[3], b[3];
    {
        int    i, j, k;
        double    tmp1[3][3];
20      double    tmp2[3][3];

        for (i = 0; i < 3; i++) {
            for (j = 0; j < 3; j++) {
25              tmp1[i][j] = a[i][j];
              tmp2[i][j] = b[i][j];
            }
        }

        for (i = 0; i < 3; i++) {
30          for (j = 0; j < 3; j++) {
              c[i][j] = 0;
              for (k = 0; k < 3; k++) {
                  c[i][j] += tmp1[i][k] * tmp2[k][j];
35              }
          }
        }
    }

    mtrans(a)
40      double          a[3];
    {
        double          tmp;

45      tmp = a[0][1]; a[0][1] = a[1][0]; a[1][0] = tmp;
        tmp = a[0][2]; a[0][2] = a[2][0]; a[2][0] = tmp;
        tmp = a[1][2]; a[1][2] = a[2][1]; a[2][1] = tmp;
    }

```

```
mnorm(a)
    double    a[3];
{
    int    i;
5      for (i = 0; i < 3; i++) {
        vnorm(a[i]);
    }
10 }
ds1/206215.2
```

## Appendix B

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```

5  /*
   rare2.e
   T2 RARE

   K. Oshio 5-26-1993

10  -----5.2-----
   5-26-1993    se -> re
   7-5-1993     phase fix
   7-8-1993     rect. nopwrap
15  7-8-1993     chem sat amp (flip_rfcssat = 110)
   7-9-1993     512. ysize fix
   7-10-1993    re -> rare2
   7-27-1993    YPOS
   10-05-1993   <math.h> (SpSat etc)
20  -----5.3-----
   1-18-1994    5.2 -> 5.3 (+ indent)
   1-18-1994    pass_lp(), slice_lp()
   2-15-1994    48 etl (time_ssi = 4000)
   2-15-1994    a_gyl fix (eg_phaseres->yres)
25  2-19-1994    watchdogcount increased (works)
   9-13-1994    3/4 fov etc for cholangiography
   9-13-1994    r1-r9, rotate for plane correction
   -----5.4-----
   2-22-1995    frame rotation
30  4-4-1995     Prescan update (Prescan.e / grad_rf_data.h)
   4-4-1995     gzk fix
   4-8-1995     Prescan/gzk (works ... not sure about scaling)
   4-11-1995    scaling fixed (MAX_ENTRY_POINTS = 9)
   8-2-1995     Dixon
35  8-5-1995     KOChemSAT

   ----- plans -----

   ----- bugs -----
40  - nopwrap (7-15-95)
   - multi-pass ... ssi_time

   */

45  @inline epic.h

   @global

```

```

#include <math.h>
#include "em_psd_ermes.in"
#include "stddef.h"
#include "epicconf.h"
5  #include "pulsegen.h"
#include "filter.h"

FILTER_INFO  echol_filt;  /* filter info struct */

10  /* PSD_FILTER_GEN psd_filt_spec[4];  /* defined in epic.h */

static char  supfailfmt[] = "Support routine %s failed";

/* Array to hold max B1 for each entry point. */
15  #define MAX_ENTRY_POINTS 9
float        maxB1[MAX_ENTRY_POINTS];
float        maxB1Seq;

20  @inline SpSat_b1scale.e      SpSatGlobal
@inline KOChemSat.e      ChemSatGlobal
int          debugstate = 0; /* printdbg() on/off */

@ipgexport
25  int        off_rfcsz[DATA_ACQ_MAX];  /* used in preprocessor */
/* generated code */

/* -CV- */
@cv
30  @inline SpSat_b1scale.e      SpSatCV
@inline KOChemSat.e      ChemSatCV

/* main */
int          time_ssi = 4000us;  /* was 250us (orig), 2000 (5.2) */
int          queue_size = 4096;  /* was 200 (orig), 1024 (5.2) */
35  int        watchdog_count = 3;  /* (x5sec) default=1 ? */
int          id0 = GRAD_UPDATE_TIME; /* cardiac delay */
int          tlead = 1ms;  /* init dead time */
int          pos_start;  /* start of pseq (excluding sat) */
int          dbg = 1;  /* same as 4x, 0:CPMG, 1:RARE */
40  int        use_ermes;  /* error message (should be in epic.h) */
int          bw_rf1;
int          bw_rf2;  /* RF pulse bandwidth */
int          pw_ramp = 500us; /* default ramp width */
int          pw_fram = 500us;  /* fast ramp */
45  int        scanslot = 1;  /* 8msec filter */
float        area_gz1;
float        ob_target;

```

```

int      trig_code = TRIG_LINE;
int      act_tr;
int      dda = 2;      /* disdaq */
int      yres;        /* actual YRES */
5  int      recno = -1; /* receiver #, -1 for all 0:L, 1:R */
int      etc;         /* effective TE */
int      nshot;
int      slicecnt = 0; /* slices B4 pause (grass) */
int      slice_size;
10 int      dixon_delay = 0;

/* CVs for Assymetric FOV */
int      transformsize;
float     phasefov;
15

/* CVs for oddnex cases... */
int      oddnex;      /* flag for oddnex case */
int      oddnex_npw;  /* flag for oddnex and npw case */
int      evennex_npw; /* flag for evennex and npw case */
20

/* rotation */
int      rot_fix = 0; /* 0: no correction. 1: correction */
float     f_shift = 0; /* trans vector (mm) */
float     p_shift = 0; /* trans vector (mm) */
25 float     z_shift = 0; /* trans vector (mm) */
float     r11 = 1.0; /* rot matrix */
float     r22 = 1.0; /* rot matrix */
float     r33 = 1.0; /* rot matrix */
float     r12 = 0; /* rot matrix */
30 float     r23 = 0; /* rot matrix */
float     r13 = 0; /* rot matrix */
float     r21 = 0; /* rot matrix */
float     r32 = 0; /* rot matrix */
float     r31 = 0; /* rot matrix */
35

/* rh cvs */
short     autolock = 0;
short     blank = 4;
short     nograd = 0;
40 short     nofermi = 0;
short     rawdata = 0;
short     saveinter = 0;
short     zchop = 1;
short     ceepf = 0;
45 short     oeepf = 0;
short     ceff = 0;
short     oeff = 0;

```

```

short      nreceiver = 1;
int         num_conc_grad = 3;

/* adv panel */
5  int      min_seq1;
   int      min_seq2;
   int      min_seq3;
   int      tmin_total;
10  int      max_gyl;

/* prescan */
@inline Prescan.e      PScvs
short      pre_pass = 0; /* ps pass# */
short      pre_slice = 0; /* ps slice# */
15

@host
#include "sar_pm.h"
#include "grad_rf_data.h"
@inline Prescan.e      PShost
20

abstract("T2 weighted RARE");
psdname("rare2");

/* -CVINIT- */
25  int
   cvinit()
   {
   #ifdef ERMES_DEBUG
   use_ermes = 0;
30  #else
   use_ermes = 1;
   #endif
   #include "cvinit.in"

35  /* config var ? */
   EpicConf();

/* init opcv */
   pititle = 0;
40   piuset = use0;
   cvdesc(pititle, "User Variables");
   opuser0 = 0.0;
   cvmax(optr, 30s);
   cvmax(ihtr, 30s);
45   cvmax(opslthick, 100); /* for projection */
   cvmax(opfast, 1);      /* enable fast option */
   cvmax(opmph, 1);      /* enable multi-phase option */

```

```

        cvdef(opirmode, 0);    /* non-sequential */
        cvmax(oprbw, 32);    /* default max = 16 */
        oprbw = 32.0;
        cvdef(opetl, 7);
5       cvdef(opte, 18ms);
        ete = opte * (opetl + 1) / 2;
        cvdef(opxres, 256);
        cvdef(opyres, 256);
        fn = 1;    /* init */
10      /* init for oddnex flags */
        oddnex_npw = 0;
        oddnex = 0;
        evennex_npw = 0;
15      truenex = 0;

        /* ramp (-d = -a), others are set auto */
        amptarget(&ob_target, num_conc_grad):
        pw_gzrf1a = pw_ramp;
20      pw_gzrf1d = pw_ramp;
        pw_gzrf2a = pw_ramp;
        pw_gzrf2d = pw_ramp;

        /* trans spoiler */
25      pw_gzk = 4ms;
        pw_gzka = pw_ramp;
        pw_gzkd = pw_ramp;

        /* RF (has to be consistent with grad_rf.h) */
30      /* (these have to be initialized even if not used */
        pw_rf1 = 3200;
        pw_rf2 = 3200;
        pw_rf22 = 3200;
        pw_gzrf1 = pw_rf1;
35      pw_gzrf2 = pw_rf2;
        pw_gzrf22 = pw_rf2;
        cyc_rf1 = 1.0;
        cyc_rf2 = 1.0;
        cyc_rf22 = 1.0;
40      gscale_rf1 = 0.9;
        gscale_rf2 = 0.9;
        gscale_rf22 = 0.9;

        /* readout */
45      echol_filt = fl6;    /* copy struct */

        /* advisory panel */

```



```

    piadvise = 1;
    piadvmin = (1 << PSD_ADVTE) + (1 << PSD_ADVTR) + (1 << PSD_ADVFOV);
    piadvmax = (1 << PSD_ADVTE) + (1 << PSD_ADVTR) + (1 << PSD_ADVFOV);
    piadvtime = (1 << PSD_ADVDMINTSCAN) + (1 <<
5   PSD_ADVMAXLOCSPERACQ)
      + (1 << PSD_ADVDMINACQS) + (1 << PSD_ADVMAXYRES);
    avminslquant = 1;
    avmaxte = 500ms;
    avmaxtr = 10s;
10   avmaxfov = 480;

    /* SAT */
    vrgsat = SINC_SAT;
    SpSatInit(vrgsat);
15   /* ChemSAT */
    @inline KOChemSat.e    ChemSatInit

    /* PS */
20   PScvinit();
    AScvinit();

    return SUCCESS;
} /* cvinit() */
25   @inline SpSat_blscale.e    SpSatInit
    @inline SpSat_blscale.e    SpSatCheck

    /* -FILTER- */
30   int
    calc_filter(info, bw, res, slot)/* make filter (move to lib) */
    {
        FILTER_INFO    *info; /* output */
        float          bw; /* bandwidth */
        int             res; /* xres */
35         int           slot; /* slot number to use */
        {
            float        abw;
            int           taps;
            int           prefill;
40         PSD_FILTER_GEN *spec;

        /* calc info */
        if (bw <= 0.0) {
            info->fslot = 0;
            return FAILURE;
45         } else {
            info->decimation = 64 / (int)bw;

```

```
        if (info->decimation == 0)
            info->decimation = 1;
        abw = 64.0 / (float)info->decimation;
        info->bw = abw * 10.0 / 10.0; /* round to 0.1 kHz */
5      info->tdaq = res * info->decimation * PSD_TSP;
        info->fslot = slot;
        info->fname = 0;
    }

10  /* filter gen */
    if (info->fslot < 4 || info->fslot > 8)
        return FAILURE;
    spec = &psd_filt_spec[0];
    psd_filt_spec[1].filter_slot = 0;
15  psd_filt_spec[2].filter_slot = 0;
    psd_filt_spec[3].filter_slot = 0;
    switch (info->decimation) { /* Empirical measured values */
    case 1:
20      taps = 67; /* not tested yet */
        break;
    case 2:
        taps = 67;
        break;
    case 3:
25      taps = 102;
        break;
    case 4:
        taps = 180;
        break;
30  case 5:
        taps = 201;
        break;
    default: /* Anything past 255 taps. Who cares? */
35      taps = 255;
        break;
    }
    prefill = (taps + 1) / 2 - 1;

    spec->filter_slot = info->fslot;
40  spec->taps = taps;
    spec->dec = info->decimation;
    spec->outputs = res;
    spec->prefills = prefill;
    spec->flush = 0;
45  spec->tflush = 0;
    spec->post_flush = 0;
    spec->queuing = 0;
```

```

spec->rshift = 0;
spec->alp = 0.46;

if (spec->dec & 0x01) /* quadrature detection */
5   spec->det = 0; /* if odd must do hardware detection */
else
    spec->det = 1; /* if even can do coefficient detection */
if (spec->dec == 1) /* for filters with no decimation */
    spec->dfg = 1.0; /* must use unitary gain */
10   else /* otherwise use gain of 2.0 */
        spec->dfg = 2.0; /* This is a bug that will be fixed. */
/* (says Bruce Collick) */
spec->filfrq = bw;
spec->picw = 0.985;
15   spec->wt = 1.0;
spec->invert_q = 0;
return SUCCESS;
} /* calc_filter() */

20   /* -CVEVAL- */
int
cveval()
{
    int          status;
25   int          av_temp_int;

    /* screen control */
    /* flip angle */
    pifanub = 0;
30   pifaval2 = 10;
    pifaval3 = 20;
    pifaval4 = 30;
    pifaval5 = 45;
    pifaval6 = 60;
35   /* NECHO */
    piechnub = 0; /* number */
    piechval1 = 1;
    piechval2 = 2;
40   /* TE */
    pitelnum = 63; /* ##### */
    pitelval2 = 12ms; /* or make this PSD_MINFULLTE */
    pitelval3 = 15ms;
    pitelval4 = 18ms;
45   pitelval5 = 20ms;
    pitelval6 = 30ms;

```

```

/* ETL */
    pietlnub = 63;
    pietlval2 = 5;
    pietlval3 = 7;
5    pietlval4 = 11;
    pietlval5 = 15;
    pietlval6 = 64;

/* TE2 */
10    pite2nub = 0;

/* TR */
    pitrnub = 6;      /* number */
    pitrval2 = 500ms;
    pitrval3 = 2000ms;
15    pitrval4 = 2500ms;
    pitrval5 = 3000ms;
    pitrval6 = 4000ms;

/* NEX */
20    pinexnub = 57;      /* # . . # # # */
    pinexval4 = 1;
    pinexval5 = 2;
    pinexval6 = 4;
25

/* XRES/YRES */
    pixresnub = 6;      /* . # . . . . */
    piyresnub = 62;     /* . # # # # # */

/* bandwidth */
30    pircbnub = 0;      /* number */
    pircb2nub = 0;
    pircbval2 = 32.0;
    pircbval3 = 16.0;
35

/* multi-phase */
    if (opmph == PSD_ON) {
        pimphscrm = 1;
        pifphasenub = 6; /* number */
40        pifphaseval2 = 1;
        pifphaseval3 = 2;
        pifphaseval4 = 5;
        pifphaseval5 = 10;
        pifphaseval6 = 15;
45    } else {
        pimphscrm = 0;
        pifphasenub = 0;
    }

```

```

    }
    if (opfphases == 1) {
        pisldeInub = 0;
        piacqnub = 0;
5      } else {

        pisldeInub = 6;
        pisldeInub3 = 500ms;
        pisldeInub4 = 1000ms;
10       pisldeInub5 = 2000ms;
        pisldeInub6 = 5000ms;

        piacqnub = 2;
    }
15
    /* Variable FOV buttons on or off depending on square pixels */
    if ((exist(opsquare) == PSD_ON) || (exist(opnopwrap) == PSD_ON)) {
        piphasfovInub = 0;
    } else {
20       piphasfovInub = 7;
    }

    /**** Asymmetric Fov ****/
    /* handling for phase (y) resolution and recon scale factor.*/
25     if ((exist(opnopwrap) == PSD_ON) && existcv(opnopwrap)) {
        rhphasescale = 1.0;
        setexist(opphasefov, PSD_ON);
        _opphasefov.fixedflag = 0;
        opphasefov = 1.0;
30       _opphasefov.fixedflag = 1;
        eg_phaseres = exist(opyres);
    } else if ((exist(opsquare) == PSD_ON) && existcv(opsquare))
    {
        rhphasescale = (float)exist(opyres)/(float)exist(opxres);
35       setexist(opphasefov, PSD_ON);
        _opphasefov.fixedflag = 0;
        opphasefov = rhphasescale;
        _opphasefov.fixedflag = 1;
        eg_phaseres = exist(opxres);
40     }
    else if ((exist(opphasefov) != 1.0)
        && existcv(opphasefov)
        && (exist(opsquare) != PSD_ON)
        && existcv(opsquare)) {
45       rhphasescale = exist(opphasefov);
        eg_phaseres = exist(opyres);
    } else {

```

```

        rhphasescale = 1.0;
        _opphasefov.fixedflag = 0;
        opphasefov = 1.0;
        _opphasefov.fixedflag = 1;
5      eg_phaseres = exist(opyres);
    }

    /* multi-coil */
    if (recno == -1) {
10      rhdab0s = cfrecvst;
        rhdab0e = cfrecvend;
    } else {
        rhdab0s = recno;
        rhdab0e = recno;
15    }
    nreceiver = rhdab0e - rhdab0s + 1;

    /* slice order type */
    if (seqtype(&seq_type) == FAILURE) {
20      epic_serror("seqtype() failed");
        return FAILURE;
    }
    acq_type = TYPSPIN;

25  /* chem sat */
    if (ChemSatEval(&cs_satime) == FAILURE) {
        epic_serror("ChemSatEval() failed");
        return FAILURE;
    }

30  /* KOChemSat.e will handle these
    cs_satime = RUP_GRD(pw_rfcssat + pw_gykcsa + pw_gykcs + pw_gykcsd)
        + 1ms;
    if (!cs_sat)
        cs_satime = 0;
35  flip_rfcssat = 110.0;
    */

    /* sp sat */
    if (SpSatEval(&sp_satime) == FAILURE) {
40      epic_serror("Spatial Sat eval failed");
        return FAILURE;
    }

    /* RF1, RF2 */
45  bw_rf1 = 4.0 * cyc_rf1 / (pw_rf1 / (float)1.0s);
    bw_rf2 = 4.0 * cyc_rf2 / (pw_rf2 / (float)1.0s);
    if (ampslice(&a_gzrf1, bw_rf1, opslthick,
        gscale_rf1, TYPDEF) == FAILURE) {

```

```

        epic_serr("ampslice failure for gzf1");
    }
    if (ampslice(&a_gzf2, bw_rf2, opslthick,
5         gscale_rf2, TYPDEF) == FAILURE) {
        epic_serr("ampslice failure for gzf2");
    }
    a_gzf22 = a_gzf2;

/* crusher / ramp */
10 /* opramp(&pw_gzf1a, a_gzf1, 1, TYPDEF); */
    pw_gzf1d = pw_gzf1a;

    pw_gzf2r = 1200;
    pw_gzf22l = 1200;
15 pw_gzf22r = 1200;
    a_gzf2r = 0.9;
    a_gzf22l = 0.9;
    a_gzf22r = 0.9;
    opramp(&pw_gzf2ra, a_gzf2r, 1, TYPDEF);
20 pw_gzf2rd = pw_gzf2ra;

    pw_gzf2a = pw_gzf2ra;
    pw_gzf2d = pw_gzf2ra;
    pw_gzf2la = pw_gzf2ra;
25 pw_gzf2ld = pw_gzf2ra;
    pw_gzf22a = pw_gzf2ra;
    pw_gzf22d = pw_gzf2ra;
    pw_gzf22la = pw_gzf2ra;
    pw_gzf22ld = pw_gzf2ra;
30

    pw_gzf22ra = pw_gzf2ra;
    pw_gzf22rd = pw_gzf2ra;

    area_gz1 = (pw_gzf1 + pw_gzf1d) * a_gzf1 / 2.0;
35 if (amppwlcsh(&gradz[GZRF2L_SLOT], &gradz[GZRF2R_SLOT],
        area_gz1, a_gzf2, ob_target) == FAILURE) {
        epic_serr("amppwlcsh failure for gzf2");
    }
/* read bandwidth / filter */
40 if (exist(opfov) < 160)
    oprbw = 16.0;
    else
        oprbw = 32.0;
    if (oprbw == 16.0 && exist(opxres) == 256) { /* default filter */
45     scanslot = 1;
        echol_filt = f16;
    } else { /* real time filt gen */

```

```

        scanslot = 4;
        calc_filter(&echol_filt, oprbw, exist(opxres), scanslot);
    }

5  /* read/phase amp */
    if (optr > 3s) dda = 0;
    else          dda = 2;

    if (opetl > 32) time_ssi = 8ms;
10  else          time_ssi = 4ms;

    /* nop */
    if (exist(opnopwrap) == PSD_ON) nop = 2;
    else          nop = 1;

15  /* yres / nshot */
    rhnframes = opyres * fn * nop * opphasefov;
    rhnframes = rhnframes / opetl / 2 * opetl * 2;
    if (rhnframes == 0) rhnframes = opetl; /* single shot */
20  yres = rhnframes / opphasefov;

    if (dbg == 0) { /* CPMG */
        nshot = rhnframes;
        rhnecho = opetl;
        ete = exist(opie);
25  } else { /* RARE */
        nshot = rhnframes / opetl;
        rhnecho = opnecho;
        ete = exist(opie) * (opetl + 1) / 2;
30  }

    if (amppwencode(&a_gyl, &pw_gyl, /* nop is float */
        exist(opfov), yres / (int)nop, 16ms, 3) == FAILURE) {
        epic_serror("amppwencode call failed");
35  }

    if (ampfov(&a_gxw, oprbw, exist(opfov)) == FAILURE) {
        epic_serror("ampfov call failed");
    }

    pw_gxw = echol_filt.tdaq;
40  a_gyla = a_gyl;
    a_gyl = -a_gyla;
    pw_gyla = pw_gyl;
    if (opramp(&pw_gxwa, a_gxw, 1, TYPDEF) == FAILURE) {
        epic_serror("opramp call failed");
45  }
    pw_gxwd = pw_gxwa;

```



```

/* pause (grass) */
    if (exist(opsliceent) == 0) {
        sliceent = exist(opslquant);
    } else {
5        sliceent = exist(opsliceent);
    }

/* adv panel */
    avminnecho = 1;
10    avmaxnecho = 1;
    min_seq1 = pw_rf1 / 2 + pw_gzrf1d /* 90 - 180 */
        + pw_gzrf2la + pw_gzrf2l
        + pw_gzrf2a + pw_gzrf2 / 2;
    min_seq2 = pw_rf2 + pw_gyl * 2 + pw_gxw; /* 180 - 180 */
15    min_seq3 = pw_gzrf2 / 2 /* 180 - read */
        + pw_gzrf2ra + pw_gzrf2r + pw_gzrf2rd
        + pw_gxw / 2;
    if (mintel(&avmintel, eg_phaseres, exist(opfov),
        min_seq1, min_seq2, min_seq3,
20    TYPSPIN, TYPNVEMP, echol_filt.tdaq,
        pw_rf1, pw_rf2, TYPNFC, 1.0) == FAILURE) {
        epic_serror("mintel failed");
        return FAILURE;
    }
25    avmaxte = ete;
    tmin_total = tlead + td0 + sp_sattime + cs_sattime
        + pw_gzrf1a + pw_rf1 / 2
        + exist(opte) * opetl
        + pw_gxw / 2 + pw_gxwd
30    + pw_gzka + pw_gzk + pw_gzkd;
    if (mintr(&avmintr, seq_type,
        (long)tmin_total, 1, trig_code) == FAILURE) {
        return FAILURE;
    }
35    max_gyl = exist(opte) - pw_rf1 / 2 - pw_gxw / 2;
    if (minfov(&avminfov, exist(opfov), seq_type, max_gyl, 1s,
        echol_filt.bw, exist(opyres), TYPNFC, pw_gxw, 1.0) == FAILURE) {
        return FAILURE;
    }
40    if (maxyres(&av_temp_int, ob_target, max_gyl) == FAILURE) {
        return FAILURE;
    }
    if ((avmaxslquant = (int)(optr / avmintr)) == 0)
        return FAILURE;
45    slice_size = (1 + rhnframes + rhhnover) * 2
        * rhpsize * rhfrsize * exist(opnecho) * nreceiver;
    maxslquanttps(&av_temp_int,

```

```

        (int)rhimsize. 1, (int)rhdayres. slice_size);
    if (av_temp_int < avmaxslquant)
        avmaxslquant = av_temp_int;
    if (opirmode == PSD_SEQMODE_ON)
5       avmaxslquant = 1;
    acqs = (opslquant - 1) / avmaxslquant + 1;    /* # of passes */
    slicein1(&slquant1, acqs, acq_type);    /* # of slices in pass 1 */
    avmaxacqs = acqs;
    avmintscan = optr * nshot;    /* time for INEX */
10    piscum4 = avmintscan;
    piscum5 = avmintscan * 2;
    piscum6 = avmintscan * 4;

    /* check current value */
15    if (exist(optr) < avmintr || exist(opte) < avminte)
        return FAILURE;

    /* prescan */
    if (PScveval() == FAILURE) return FAILURE;
20    if (AScveval() == FAILURE) return FAILURE;

    return SUCCESS;
} /* cveval() */

25 /* -CVCHECK- */
int
cvcheck()
{
    if (exist(opte) < avminte
30        || exist(optr) < avmintr
        || exist(opfov) < avminfov)
        /* this shouldn't happen. checked in cveval() */
        return FAILURE;

35    return SUCCESS;
} /* cvcheck() */

/* -PREDOWNLOAD- */
int
40 predownload()
{
    int        i;

    sp_satstart = RUP_GRD((int)tlead + GRAD_UPDATE_TIME);
45    cs_satstart = sp_satstart + sp_sattime + 1ms;
    pos_start = sp_satstart + sp_sattime + cs_sattime;

```

```

/* multi-slice */
    if (orderslice(seq_type, opslquant,
        slquant1, trig_code) == FAILURE) {
        epic_error("orderslice call failed");
5    }
    pitr = ps1_tr; /* PS1 TR */
    pichop = 0; /* No chop */
    pitsp1 = f2.decimation * PSD_TSP; /* Sample time for CFL */
    pitsp2 = f500.decimation * PSD_TSP; /* Sample time for CFH */
10    pislquant = slquant1; /* # of 2nd pass slices */

    baseline = 0;
    nex = opnex;
    exnex = opnex;
15

/* scan time */
    act_tr = RDN_GRD(optr / slquant1);
    if (opsliceent == 0) {
        pidmode = PSD_CLOCK_NORM;
20    } else {
        pidmode = PSD_CLOCK_PAUSE;
    }
    pitscan = (nshot + dda) * optr * opnex * acqs; /* clock */

25 /* image anotation */
    ihtr = optr;
    ihtel = ete;
    ihflip = opflip;
    ihnex = opnex;
30    ihvbw1 = oprbw;

/* entry table */
    if (entrytabinit(entry_point_table, (int)ENTRY_POINT_MAX)
        == FAILURE) {
35        epic_error("Can't initialize entry point table.");
        return FAILURE;
    }
    entry_point_table[L_SCAN].epfilter = scanslot;
    entry_point_table[L_APS1].epfilter = F16_SLOT;
40    entry_point_table[L_CFH].epfilter = F500_SLOT;
    entry_point_table[L_CFL].epfilter = F2_SLOT;

    entry_point_table[L_MPS1] = entry_point_table[L_APS1];
    entry_point_table[L_APS2] = entry_point_table[L_MPS2] =
45    entry_point_table[L_SCAN]; /* copy scan into APS2 & MPS2 */
    strcpy(entry_point_table[L_SCAN].epname, "scan");
    strcpy(entry_point_table[L_CFH].epname, "cfh");

```

```

        strcpy(entry_point_table[L_CFL].epname, "cfl");
        strcpy(entry_point_table[L_APS1].epname, "aps1");
        strcpy(entry_point_table[L_MPS1].epname, "mps1");
5      strcpy(entry_point_table[L_APS2].epname, "aps2");
        strcpy(entry_point_table[L_MPS2].epname, "mps2");

#include "predownload.in"

/* !!! NOT included in macro !!!! */
10   ia_gylw = ia_gyl;
    ia_gylaw = ia_gyla;

/* RF pulses are scaled by entry point basis */
    maxB1Seq = 0.0;
15   for (i = 0; i < MAX_ENTRY_POINTS; i++) {
        if (peakB1(&maxB1[i], i, RF_FREE, rfpulse) == FAILURE) {
            epic_error(use_ermes, supfailfmt,
                       EM_PSD_SUPPORT_FAILURE,
20             1, STRING_ARG, "peakB1");
            return FAILURE;
        }
        if (maxB1[i] > maxB1Seq)
            maxB1Seq = maxB1[i];
    }
25   if (setScale(L_SCAN, RF_FREE, rfpulse, maxB1[L_SCAN],
               maxB1[L_SCAN] / maxB1Seq) == FAILURE) {
        epic_error(use_ermes, supfailfmt, EM_PSD_SUPPORT_FAILURE,
                   1, STRING_ARG, "setScale");
        return FAILURE;
30   }
    ia_rf1 = max_pg_iamp * (*rfpulse[RF1_SLOT].amp);
    ia_rf2 = max_pg_iamp * (*rfpulse[RF2_SLOT].amp);

/* debug
35   if (exist(opsatx) > 0)
        ia_rfsx1 = max_pg_iamp * (*rfpulse[RFSX1_SLOT].amp);
        ia_rfsx2 = max_pg_iamp * (*rfpulse[RFSX2_SLOT].amp);
    if (exist(opsaty) > 0)
        ia_rfsy1 = max_pg_iamp * (*rfpulse[RFSY1_SLOT].amp);
40   ia_rfsy2 = max_pg_iamp * (*rfpulse[RFSY2_SLOT].amp);
    if (exist(opsatz) > 0)
        ia_rfsz1 = max_pg_iamp * (*rfpulse[RFSZ1_SLOT].amp);
        ia_rfsz2 = max_pg_iamp * (*rfpulse[RFSZ2_SLOT].amp);
*/
45   /* sat */
    SpSatIAmp(0);

```

```

        SatPlacement(acqs);
        if (cs_sat == PSD_ON)
            ia_rfcssat = max_pg_iamp * (*rfpulse[RFCSSAT_SLOT].amp);

5    /* prescan */
        if (prescanslice(&pre_pass, &pre_slice, opslquant) == FAILURE) {
            epic_error("Can't select a slice for prescan.");
            return FAILURE;
        }
10    PSpredownload();
    ASpredownload();

    /* ===== recon header variables ===== */
    /* rhtype */
15    rhtype = 0;
    if (nex > 1)
        rhtype |= RHTYPCHP;
    if (opimode == PSD_CINE)
        rhtype |= RHTYPCINE;
20    if (oppseq == PSD_GE ||
        oppseq == PSD_TOF ||
        oppseq == PSD_TOFSP ||
        oppseq == PSD_PC ||
        oppseq == PSD_PCSP)
25        rhtype |= RHTYPGR;
    if (fn == 0.5)
        rhtype |= RHTYPFRACTNEX;
    if (oprect)
        rhtype |= RHTYPSTRIP;
30    if (opimode == PSD_3D)
        rhtype |= RHTYP3D;
    if (nop == 2 && oppomp == PSD_OFF)
        rhtype |= RHTYPNPW;
    if (pitfeextra > 0)
35        rhtype |= RHTYPFRACTECHO;
    if (fn == 0.75)
        rhtype |= RHTYP75NEX;
    if (oppomp)
        rhtype |= RHTYPPOMP;
40    /* rhformat */
        rhformat = nograd + 2 * nofermi;
        if (opimode == PSD_3D) {
            if (zchop)
45                rhformat |= 4;
            else
                rhformat |= 8;

```

```

    }
    if (opscic == PSD_ON)
        rhformat |= 16;

5   /* others */
    rhbline = baseline;
    rhblank = blank;
    rhfrsize = exist(opxres); /* rhnframes is in eval */
    rhnslices = opslquant * opfphases;
10   rhptsize = opptsize;
    rhnavs = lMax(2, nex / 2, 1);

    rhdacqctrl = rawdata +
        2 * eepf + /* even echo phase flip */
15   4 * oepf + /* odd echo phase flip */
        8 * eeff + /* even echo freq flip */
        16 * oeff; /* odd echo freq flip */
    rhexecctrl = 9 + 2 * autolock + 64 * saveinter;
    rhvquant = opvquant; /* VQUANT ... does this work ? */
20   rhslblank = pislblank;
    rhzeroph = (yres * nop / 2) / (1 + oprect) + 0.5;
    if (pitfeextra > 0)
        rhnwin = 8;
    else
25   rhnwin = 0;
    if (pitfeextra > 0 || (fn == 0.5) && (nop == 2))
        rhntran = 4;
    else
30   rhntran = 2;

    rhfermr = rhfrsize / 2;
    rhnpasses = acqs;

    rhrawsize = slquant1 * slice_size;
35   rhrcyres = exist(opyres);
    rhrcxres = exist(opxres);
    rhmethod = oppomp;
    rh daxres = exist(opxres);
40   rhdayres = rhnframes + rhhnover + 1;
    if (exist(opxres) > 256 || exist(opyres) > 256)
        rhimsize = 512;
    else
45   rhimsize = 256;
    rhnpasses = acqs;

    /* calculation for rhyoff with asym fov */

```

```

    phasefov = exist(opphasefov) * exist(opxres);
    transformsize = 1;
    while (transformsize < phasefov - 0.001) transformsize <<= 1;
    if (transformsize > phasefov + 0.001) transformsize = exist(opxres);
5
    return SUCCESS;
} /* predownload() */

10
    @inline KOChemSat.e    ChemSatEval
    @inline KOChemSat.e    ChemSatCheck
    @inline SpSat_b1scale.e    SpSatEval
    @inline SpSat_b1scale.e    SatPlacement

    /* -PULSEGEN- */
15
    @rsp
    /* used by pulsegen & rsp */
    CHAR          * entry_name_list[ENTRY_POINT_MAX] = {
        "scan",
        "cfl",
20
        "cfh",
        "mps1",
        "aps1",
        "mps2",
        "aps2",
25
        "autoshim",
        0};
    int          *rf1_freq, *rf2_freq;
    float        *rf1_phase, *rf2_phase;
    int          *receive_freq1;
30
    int          cs_satindex = 0; /* sat index */
    int          sp_satindex = 0; /* sat index */
    int          deadtime;      /* dead time for scan() */
    int          seqtime;       /* time/seq */

35
    short        rsprot_orig[DATA_ACQ_MAX][9]; /* rotation matrix for SAT */
    /* array to store calculated phase offset and sign */
    typedef struct {
        int ysign;      /* sign of the phase offset */
        int yoffs;      /* calculated phase offset from rsp_info structure */
40
    } PHASE_OFF;

    PHASE_OFF    phase_off[DATA_ACQ_MAX];
    int          yres_phase;      /* offset in phase direction in mm */
    int          yoffs1;         /* intermediate phase offset variable */
45
    WF_PULSE     *echol;
    float        orig_rot[3][3]; /* original rotation matrix */

```

```

RSP_INFO      *rsp_shift;    /* copy rsp_info. and shift */

int
ssisat()
5  {
    int next_slice;

    next_slice = sp_sat_index;
    sp_update_rot_matrix(&rsprot_orig[next_slice][0], sat_rot_matrices,
10    sat_rot_ex_num, sat_rot_df_num);

    /* if (opexor == PSD_ON) exorcist_ssi(); */

    return SUCCESS;
15 }

int
dummyssi()
{
20     return SUCCESS;
}

@pg
pulsegen()
25 {
    int      echo: /* echo index */
    int      rf2loc; /* center of 180 */
    char      pname[256];
    int      i, j, ix;
30

    /* set watchdog timer */
    setwatchdogrsp(watchdog_count);

    /* trigger delay (modify period to put delay) */
35     WAIT(XGRAD, x_td0, tlead, GRAD_UPDATE_TIME);
    WAIT(YGRAD, y_td0, tlead, GRAD_UPDATE_TIME);
    WAIT(ZGRAD, z_td0, tlead, GRAD_UPDATE_TIME);
    WAIT(RHO, rho_td0, tlead, GRAD_UPDATE_TIME);
    WAIT(THETA, theta_td0, tlead, GRAD_UPDATE_TIME);
40     WAIT(SSP, ssp_td0, tlead, GRAD_UPDATE_TIME);

    /* SpSAT */
    sp_satindex = 0;
    SpSatPG(vrgsat, sp_satstart, &sp_satindex, sp_satcard_loc);
45

    /* ChemSAT */
    cs_satindex = 0;

```



```

        if (cs_sat) ChemSatPG(cs_satstart, &cs_satindex);

/* --- seqcore ----- */
/* 90 / dephaser */
5   SLICESELZ(rf1,
        pos_start + pw_gzrf1a,
        pw_rf1, opslthick, opflip, cyc_rf1, TYPNDEF);
    TRAPEZOID(XGRAD, gx1,
        pend(&rf1, "gzrf1", 0) + pw_gx1a,
10   a_gxw * (pw_gxw + pw_gxwa) / 2.0, TYPDEF);

/* alloc mem for DAB packets */
    echol = (WF_PULSE *) AllocNode((opetl + 2) * sizeof(WF_PULSE));

15 /* echo train */
    rf2loc = pmid(&rf1, "gzrf1", 0) + opte / 2;
    for (echo = 0; echo < opetl; echo++) {
        if (echo == 0) /* first echo */
            SLICESELZ(rf2,
20         rf2loc - pw_gzrf2 / 2, pw_rf2,
            opslthick, 180, cyc_rf2, TYPNDEF);
        TRAPEZOID(ZGRADB, gzrf2l,
            pbeg(&rf2, "gzrf2a", 0) - pw_gzrf2l,
            0, TYPNDEF);
25         TRAPEZOID(ZGRADB, gzrf2r,
            pend(&rf2, "gzrf2d", 0),
            0, TYPNDEF);
        } else {
            SLICESELZ(rf22,
30         rf2loc - pw_gzrf2 / 2, pw_rf2,
            opslthick, 180, cyc_rf2, TYPNDEF);
        TRAPEZOID(ZGRADB, gzrf22l,
            pbeg(&rf22, "gzrf22a", echo - 1) - pw_gzrf22l,
            0, TYPNDEF);
35         TRAPEZOID(ZGRADB, gzrf22r,
            pend(&rf22, "gzrf22d", echo - 1),
            0, TYPNDEF);
        }
    }

40   TRAPEZOID(XGRAD, gxw,
        rf2loc + opte / 2 - pw_gxw / 2 + dixon_delay,
        0, TYPNDEF);
    SINUSOID(YGRAD, gyl,
        pbeg(&gxw, "gxw", echo) - pw_gyl, pw_gyl,
45   a_gyl, 0, 0.0, 0.5, 0.0);
    SINUSOID(YGRAD, gyla,
        pend(&gxw, "gxw", echo), pw_gyla.

```

```

        a_gyla. 0. 0.0, 0.5, 0.0);

/* DATA ACQ */
5       sprintf(pname, "echo1_%02d", echo);
       pulsename(&(echo1[echo]), pname);
       acqq(&(echo1[echo]),
           pbeg(&gxw, "gxw", echo) + psd_grad_acq_delay,
           scanslot, recno, DABNORM, PASSTHROUGH);
10      rf2loc += opte;
    }

/* killer */
    TRAPEZOID(ZGRAD, gzk,
15      pend(&gxwd, "gxwd", opetl - 1) + pw_gzka,
      0, TYPNDEF);

/* define sequence */
    SEQLength(seqcore, act_tr, seqcore);
    getperiod(&deadtime, &seqcore, 0);
20    seqtime = act_tr - deadtime;

/* ----- prescan ----- */
    PSpulsegen();
    ASpulsegen();
25

/* pass */
    PASSPACK(pass_pulse, 49ms); /* tell Signa system we're done */
    SEQLength(seqpass, 50ms, seqpass);

30 /*sequencer memory alloc (original size) */
    ipg_alloc_instr[0] = 2048; /* XGRAD (816) */
    ipg_alloc_instr[1] = 2048; /* YGRAD (816) */
    ipg_alloc_instr[2] = 2048; /* ZGRAD (816) */
    ipg_alloc_instr[3] = 2048; /* RHO1 (816) */
35    ipg_alloc_instr[4] = 2048; /* RHO2 ( 64) */
    ipg_alloc_instr[5] = 2048; /* THETA (816) */
    ipg_alloc_instr[6] = 2048; /* OMEGA (816) */
    ipg_alloc_instr[7] = 2048; /* SSP (1024) */
    ipg_alloc_instr[8] = 64; /* AUX ( 64) */
40

/* build instruction */
    if (buildinstr() == FAILURE)
        return FAILURE;

45 /* Calculate the RF & slice frequencies */
    rf1_freq = (int *)AllocNode((opslquant + 2) * sizeof(int));
    rf2_freq = (int *)AllocNode((opslquant + 2) * sizeof(int));

```

```

    rf1_phase = (float *)AllocNode((opslquant + 2) * sizeof(float));
    rf2_phase = (float *)AllocNode((opslquant + 2) * sizeof(float));
    receive_freq1 = (int *)AllocNode((opslquant + 2) * sizeof(int));

5  /* rotation / translation (modify rsp_info before setting up freq etc.) */
   /* save original rot matrix (rsprot will be overwritten) */
   for (i = 0; i < 3; i++) {
       for (j = 0; j < 3; j++) {
           ix = j + 3 * i;
10      orig_rot[i][j] = (float)rsprot[0][ix];
       }
   }

   /* shift rsp_info (x, y, z) */
   rsp_shift = (RSP_INFO *)AllocNode(opslquant * sizeof(int));
15   if (rot_fix) {
       for (i = 0; i < opslquant; i++) {
           rsp_shift[i].rsptloc = rsp_info[i].rsptloc + z_shift;
           rsp_shift[i].rsprloc = rsp_info[i].rsprloc + f_shift;
           rsp_shift[i].rspphasoff = rsp_info[i].rspphasoff + p_shift;
20       }
   } else {
       for (i = 0; i < opslquant; i++) {
           rsp_shift[i].rsptloc = rsp_info[i].rsptloc;
           rsp_shift[i].rsprloc = rsp_info[i].rsprloc;
25       rsp_shift[i].rspphasoff = rsp_info[i].rspphasoff;
       }
   }

   /* Set the Slice Frequency */
30   setupslices(rf1_freq, rsp_shift, opslquant,
               a_gzrf1, (float)1, TYPTRANSMIT);
   setupslices(rf2_freq, rsp_shift, opslquant,
               a_gzrf2, (float)1, TYPTRANSMIT);

   /* multi-slice CPMG phase */
35   set_cpmg_phase(rf1_phase, rf1_freq, 0.0, pw_rf1 / 2 + 9);
   set_cpmg_phase(rf2_phase, rf2_freq, PI / 2.0, pw_rf2 / 2 + 9);

   setupslices(receive_freq1, rsp_shift, opslquant, 0.0, oprbw, TYPREC);
   setupphasetable(viewtable, TYPNORM, rhnframes); /* replace this */
40   return SUCCESS;
} /* pulsegen() */

void
45 set_cpmg_phase(phase, freq, offs, del)
    float      *phase; /* phase array (output) */
    int        *freq;  /* freq array (input) */

```

```

        float      offs; /* phase offset */
        int        del; /* time from reset to center of pulse */
    {
        int        i;
5       float      ph;

        /* doesn't matter as long as same freq are used for rf1 & rf2 */
        /* necessary for inner volume, though */

10      for (i = 0; i < opsquant; i++) {
            ph = del * freq[i] / 0.59604648; /* phase */
            ph -= (int)ph;
            phase[i] = -ph * 2.0 * PI + offs;
        }
15  }

    @inline KOChemSat.e  ChemSatPG
    @inline SpSat_b1scale.e  SpSatPG
    @inline Prescan.e      PSigg
20  /* End of @pg */

    /* -RSPVAR- */
    @rspvar
    @inline Prescan.e      PSrspvar
25  @inline KOChemSat.e  ChemSatRspVar
    @inline SpSat_b1scale.e  SpSatRspVar

    short      viewtable[513]; /* max view + 1 (base 1) */
    short      acq_ptr[256];
30  short      sle_in_acq[256];
    int        dabop; /* dab op (load, add etc) */
    int        acq_echo1; /* dab on/off */
    int        rspent, rspdda, rspbas, rspvus, rspgyl, rspasl;
    int        rspesl, rspchp, rspnex, rpslq, rpsct;
35  int        rf1Phase, seqCount; /* SPGR */
    short      chopamp;

    /* -RSP- */
    @rsp
40  @inline KOChemSat.e  CsSatMod
    @inline SpSat_b1scale.e  SpSatInitRsp
    @inline SpSat_b1scale.e  SpSatUpdateRsp
    @inline SpSat_b1scale.e  SpSatON
    @inline Prescan.e      PScore
45  /* -PSDINIT- */
    int

```

```

psdinit()
{
    int      slmod_acqs;
    int      i;

5
    /* Initialize everything to a known state */
    setrfconfig((short)5); /* only activate rho1 */
    setssitime(time_ssi / GRAD_UPDATE_TIME);
    rspqueueinit(queue_size); /* was 200 */
10
    scopeon(&seqcore); /* Activate scope for core */
    syncon(&seqcore); /* Activate sync for core */
    syncoff(&seqpass); /* Deactivate sync during pass */
    seqCount = 0; /* Set SPGR sequence counter */
    settriggerarray((short)slquant1, rsptrigger);
15
    setrotatearray((short)slquant1, rsprot);
    chopamp = ia_rfl;
    setiamp(chopamp, &rfl, 0);
    for (i = 0; i < opetl; i++) {
        setfltrs(scanslot, &echol[i]);
20
    }

    /* sat / chemsat */
    SpSatInitRsp(vrgsat, sp_satindex, sp_satcard_loc, 0);
    SpSat_set_sat1_matrix(rsprot_orig, rsprot, opslquant * opphases,
25
        sat_rot_matrices, sat_rot_ex_num, sat_rot_df_num,
        sp_satcard_loc, 0);
    setrotatearray((SHORT)(opslquant * opphases), rsprot);
    CsSatMod(cs_satindex);

30
    /* setup pass arrays */
    slmod_acqs = opslquant % acqs;
    for (i = 0; i < acqs; i++) {
        slc_in_acq[i] = opslquant / acqs;
        if (i < slmod_acqs)
35
            slc_in_acq[i] += 1;
        if (i == 0) {
            acq_ptr[i] = 0;
        } else {
            acq_ptr[i] = acq_ptr[i - 1]
40
                + slc_in_acq[i - 1];
        }
    }

    /* asym FOV - overrides previous code */
45
    /* set up phase offset arrays */
    for (i = 0; i < opslquant * opfphases; i++) {
        if (rsp_shift[i].rspphasoff >= 0) {

```

```

        phase_off[i].ysign = -1;
    } else {
        phase_off[i].ysign = 1;
    }
5   /* phase offset increment */
    yoffsl = 0.5 + fabs(FS_2PI * rsp_shift[i].rspphasoff /
        (opfov*opphasefov*nop));
    /* offset in range */
10   phase_off[i].yoffs = (yoffsl + FS_2PI + FS_PI) % FS_2PI
        - FS_PI;
    }

    sp_sat_index = 0;
    if (opsat == PSD_ON) {
15     if (ssivector(ssisat) == FAILURE) return FAILURE;
    } else {
        if (ssivector(dummyssi) == FAILURE) return FAILURE;
    }

20   return SUCCESS;
}

int
mps2()
25   {
    rspent = L_MPS2;
    rspdda = 2;
    rspbas = 0;
    rspvus = 30000;
30   rspgy1 = 0;
    rspnex = 2;
    rspesl = pre_slice;
    rspasl = pre_slice;
    rspslq = 1;
35   rspset = 0;
    cstun = 1;      /* turn chemsat on */

    psdinit();
    SpSat_Saton(0);
40   setperiod(optr - seqtime, &seqcore, 0);
    boffset(off_seqcore);
    pscore();

    return rspexit();
45   } /* mps2() */

int

```

```
aps2()
{
    rspent = L_APS2;
    rspdda = 2;
5    rspbas = 0;
    rspvus = 1024;
    rspgyl = 0;
    rspnex = 2;
    rspesl = pre_slice;
10    rspasl = pre_slice;
    rspslq = 1;
    rspset = 0;
    cstun = 1;          /* turn chemsat on */

15    psdinit();
    SpSat_Saton(0);
    setperiod(optr - seqtime, &seqcore, 0);
    boffset(off_seqcore);
    pscore();
20    return rspexit();
} /* aps2() */

/* -SCAN- */
25 int
scan()
{
    short      pause;
    int         pass;
30
    rspent = L_SCAN;
    rspset = 0;
    rspslq = slquantl;
    cstun = 1;          /* turn chemsat on */
35
    psdinit();
    SpSat_Saton(0);
    setperiod(deadtime, &seqcore, 0);

40    for (pass = 0; pass < acqs; pass++) {
        /* scan */
        boffset(off_seqcore);
        pass_lp(pass);

45    /* pass packet */
        boffset(off_seqpass);
        if (pass == (acqs - 1)) {      /* last pass, eoscan */
```

```

        setwamp(SSPD + DABPASS + DABSCAN, &pass_pulse, 2);
    } else {
        /* eopass */
        setwamp(SSPD + DABPASS, &pass_pulse, 2);
    }
5   /* pause */
    if (pass == (acqs - 1)) {
        pause = MAY_PAUSE;
    } else {
        if (((pass + 1) % sliceCnt) == 0) {
10          pause = MUST_PAUSE; /* pause if desired */
        } else {
            pause = AUTO_PAUSE; /* or if required */
        }
    }
15    sp_sat_index = 0;
    startseq(0, pause);
}
return rspexit();
}
20
int
rot_corr(sl) /* rotate */
    int      sl;
{
25    double th, cs, sn;
    float  view_rot[3][3];
    short  net_rot[9];
    int    i, j, k, ix;

30    view_rot[0][0] = r11; view_rot[0][1] = r12; view_rot[0][2] = r13;
    view_rot[1][0] = r21; view_rot[1][1] = r22; view_rot[1][2] = r23;
    view_rot[2][0] = r31; view_rot[2][1] = r32; view_rot[2][2] = r33;

    for (ix = 0; ix < 9; ix++) net_rot[ix] = 0;
35    for (i = 0; i < 3; i++) {
        for (j = 0; j < 3; j++) {
            ix = j + 3 * i;
            for (k = 0; k < 3; k++) {
40                /* net_rot[ix] += (short)
                   (orig_rot[i][k] * view_rot[k][j]); */
                   (view_rot[i][k] * orig_rot[k][j]);
            }
        }
    }
45    setrotate(net_rot, sl);

    return 0;

```



```

    }

/* -CORE- */
5   int
   pass_lp(pass)      /* spin echo core ... multi-pass */
       int            pass;
   {
       int            view; /* view index */
10      int            shot; /* excitation index */
       int            excitation; /* NEX index */
       int            i;

       for (shot = -dda; shot < nshot; shot++) {
15          for (i = 0; i < opetl; i++) {
              if (dbg == 0) {
                  view = shot;
              } else {
20                  view = i * nshot + shot;
              }
              /* phase encoding view */
              if (shot < 0) view = 0; /* if DDA */
              setiamp(viewtable[view + 1], &gyl, i);
              setiamp(viewtable[view + 1], &gyla, i);
25          }

          /* excitation loop */
          for (excitation = 0; excitation < opnex; excitation++) {
              /* DABOP and chop */
30              if (excitation == 0) {
                  dabop = 0;
              } else {
                  dabop = 1 + 2 * (excitation % 2);
              }
              getiamp(&chopamp, &rfl, 0);
              setiamp(-chopamp, &rfl, 0);
35              /* scan */
              slice_lp(pass, shot);
40          }
      }

      slice_lp(pass, shot)
45      int pass, shot;
      {
          int            view; /* view index */

```

```

float      phs;
int        yres_phase;
int        echo. i; /* echo index */
int        sl, slice; /* slice index */
5 int      dummy_flag, dda_flag;

if (shot >= 0) {
    dda_flag = PSD_ON;
} else {
10     dda_flag = PSD_OFF;
}
dummy_flag = PSD_ON;
for (sl = 0; sl < rspslq; sl++) {

15     /* rotate */
        if (rot_fix) rot_corr(sl);

    /* scope trigger */
        if (rspsc = -1 || sl == rspsc) {
20             scopeon(&seqcore);
        } else {
            scopeoff(&seqcore);
        }

25     /* dummy slice for multi-pass */
        if (sl >= slc_in_acq[pass]) {
            dummy_flag = PSD_OFF;
            setieos((short)EOS_DEAD, &rho_td0, 0);
        } else {
30             dummy_flag = PSD_ON;
            setieos((short)EOS_PLAY, &rho_td0, 0);
        }

    /* set freq and go */
35     slice = acq_ptr[pass] + sl;
        if (slice >= opslquant) slice = 0;

    /* RF freq and phase */
        setfrequency(rf1_freq[slice], &rf1, 0);
40         setfrequency(rf2_freq[slice], &rf2, 0);
        setfrequency(rf2_freq[slice], &rf22, -1);
        setphase(rf1_phase[slice], &rf1, 0);
        setphase(rf2_phase[slice], &rf2, 0);
        setphase(rf2_phase[slice], &rf22, -1);
45

    /* receiver freq and phase. DAB packet (DAB view etc) */
        if (dda_flag && dummy_flag) {

```

```

        acq_echo1 = (int)DABON;
    } else {
        acq_echo1 = (int)DABOFF;
    }
5   for (i = 0; i < opetl; i++) {
        if (dbg == 0) {
            echo = i;      /* CPMG */
            view = shot;
        } else {
10         echo = 0;      /* RARE */
            view = i * nshot + shot;
        }
        loaddab(&echo1[i], sl, echo, dabop,
15         view + 1, acq_echo1);
        yres_phase = phase_off[slice].ysign
            * ((view * phase_off[slice].yoffs
                + 3L * FS_PI)
                % FS_2PI
                - FS_PI);
20         setiphase(yres_phase, &echo1[i], i);
        setfrequency(receive_freq1[slice], &echo1[i], i);
    }

    /* startseq() */
25     sp_sat_index = sl;
        startseq(sl, (short)MAY_PAUSE);
        syncoff(&seqcore);
    }
30 }

/* -PSCORE- */
int
pscore()
{
35     int        view, i;

        setfrequency(rf1_freq[rspe1], &rf1, 0);
        setfrequency(rf2_freq[rspe1], &rf2, 0);
        setfrequency(receive_freq1[rspe1], &echo1[0], 0);
40
        dabop = 0;
        for (i = 0; i < opetl; i++) {
            loaddab(&echo1[i], 0, 0, dabop, 0, DABOFF);
        }
45     setiamp(0, &gyl, 0);

    for (view = 0; view < rspdda; view++) {

```

```

    sp_sat_index = 0;
    startseq(0, (short)MAY_PAUSE);
    getiamp(&chopamp, &rfl, 0);
    setiamp(-chopamp, &rfl, 0);
5      }
    for (view = 0; view < rspvus; view++) {
        loaddab(&echol[0], 0, 0, dabop, view + 1, DABON);
        sp_sat_index = 0;
        startseq(0, (short)MAY_PAUSE);
10       getiamp(&chopamp, &rfl, 0);
        setiamp(-chopamp, &rfl, 0);
    }
} /* pscore() */
15
ds1/206215.2
```

**WHAT IS CLAIMED IS:**

1. A method of obtaining imaging scans of a subject taken over different time periods comprising:
  - (a) taking at a first time period, using an imager, a  
5 baseline imaging scan that is relatable to a personal coordinate system (PCS) and a first machine coordinate system (MCS), which PCS can be regenerated from the subject in a substantially reproducible manner;
  - (b) taking at a different time period, using a second  
10 imager, at least one follow-up imaging scan, which scan is relatable to the PCS and a second MCS;
  - (c) manipulating the second MCS, such that the relationship between the second MCS and the PCS is substantially the same as the relationship between the first  
15 MCS and the PCS, to permit the taking of at least one additional follow-up imaging scan that can be superimposed on the baseline imaging scan.
2. The method of claim 1 which further comprises taking  
20 one or more additional follow-up imaging scans that can be superimposed on the baseline imaging scan.
3. The method of claim 1 in which the second imager of step (b) is the same as the imager of step (a).  
25
4. The method of claim 1 in which the second imager of step (b) is different from the imager of step (a).
5. The method of claim 1 in which the MSC of the imager  
30 of step (a) is fixed.
6. A method of obtaining imaging scans of a subject comprising:
  - (a) providing a subject with a non-invasive stereotactic  
35 device that is positioned reproducibly on a subject and which

establishes a personal coordinate system (PCS) associated with the subject which is independent of a machine coordinate system (MCS) associated with an imager;

(b) taking, using an imager having an MCS, an imaging  
5 scan of the subject including the stereotactic device to establish the PCS of the subject;

(c) manipulating the MCS of the imager to bring the MCS in substantial alignment with the PCS of the subject;

(d) taking one or more additional imaging scans of the  
10 subject with the MCS of the imager substantially aligned with the PCS of the subject, to obtain a first set of imaging scans.

7. The method of claim 1 which further comprises repeating steps (a) to (d) at a second time period, using a  
15 second imager, to obtain a second set of imaging scans.

8. The method of claim 7 which further comprises comparing at least one imaging scan of the first set with at least one imaging scan of the second set.

20

9. The method of claim 8 which further comprises noting any previously undetected anatomical feature of the subject.

10. The method of claim 8 which further comprises  
25 observing any changes in any previously detected anatomical feature of the subject.

11. The method of claim 9 in which said anatomical feature comprises a tumor.

30

12. The method of claim 10 in which said anatomical feature comprises a tumor.

13. The method of claim 7 in which the imagers are the  
35 same.

14. The method of claim 7 in which the imagers are different.

5        15. The method of claim 6 in which the imager is a magnetic resonance imager.

10        16. The method of claim 6 in which the stereotactic device is positioned reproducibly on the patient's head.

15        17. The method of claim 7 in which the second time period represents an elapsed time from the taking of the first set of imaging scans to the taking of the second set of imaging scans of about one day to about one week, about one week to about one month, about one month to about six months and about six months to about one year.

20        18. The method of claim 7 in which the second time period represents an elapsed time from the taking of the first set of imaging scans to the taking of the second set of imaging scans of about one year to about five years.

19. A method of obtaining imaging scans of a subject comprising:

25        (a) providing a subject with a non-invasive stereotactic device that is positioned reproducibly on a subject and which establishes a personal coordinate system (PCS) associated with the subject which is independent of a machine coordinate system (MSC) associated with an imager;

30        (b) taking, using a first imager having a first MCS, at least one imaging scan of the subject including the stereotactic device to establish the PCS of the subject and to relate the PCS of the subject to the first MCS of the first imager;

(c) taking, using a second imager having a second MCS, at least one imaging scan of the subject including the stereotactic device to reestablish the PCS of the subject and to relate the PCS of the subject to the second MCS of the  
5 second imager;

(d) manipulating the second MCS, such that the PCS is related to the second MCS in substantially the same way as the PCS is related to the first MCS.

10 20. The method of claim 19 which further comprises taking one or more additional imaging scans of the subject with the second imager.

21. The method of claim 19 which includes substantially  
15 aligning the second MCS with the first MCS.

22. The method of claim 19 in which the imagers are different.

20 23. The method of claim 22 in which the first imager is a CT scanner.

24. The method of claim 22 in which the second imager is an MR imager.

25 25. The method of claim 22 which further comprises forming a composite image including information from at least one imaging scan taken using the first imager and information from at least one imaging scan taken using the second imager.

30 26. A stereotactic device for use with an imager comprising a frame equipped with localizing means and affixing means,

the localizing means comprising one or more localizing  
35 arrays that provide one or more imager detectable signals,



the affixing means comprising non-invasive fittings for placement about the periphery of the subject and which permit the reproducible positioning of the frame on the subject,

from which signals is derived a personal coordinate system  
5 that serves as a reference coordinate system for imaging scans taken of a subject on which the frame is positioned.

27. The device of claim 26 which facilitates the stereotactic examination of the head of the subject.

10

28. The device of claim 26 in which the localizing array comprises one or more reference elements.

29. The device of claim 28 in which the reference  
15 elements are radio-opaque.

30. The device of claim 29 in which the reference elements are detectable by an MR imager.

20 31. The device of claim 26 in which the localizing means comprises four or more localizing arrays each comprising a reference element,

each reference element defining a point in space, three of which points define a unique plane and the fourth point  
25 lying outside the unique plane.

32. The device of claim 26 in which the localizing means comprises three localizing arrays each comprising a pair of reference elements.

30

33. The device of claim 32 in which the paired reference elements are arranged in a spaced-apart "X" configuration.

34. The device of claim 33 in which the paired reference  
35 elements are orthogonal to one another.

35. A stereotactic device for use with an imager comprising a frame equipped with localizing means and affixing means,

5 the localizing means comprising three or more localizing arrays each equipped with two or more reference elements that together provide six or more imager detectable signals,

the affixing means comprising three or more non-invasive fittings for placement on the subject's nasion and in or about  
10 the subject's ears and which permit the reproducible positioning of the frame on the subject,

from which signals is derived a personal coordinate system that serves as a reference coordinate system for imaging scans taken of a subject on which the frame is positioned.

15

36. The device of claim 35 in which the reference elements comprise elongate components.

37. The device of claim 36 in which two elongate  
20 components are arranged in an "X" configuration and in which the two elongate components are related to one another by a predetermined angle.

38. The device of claim 37 in which the predetermined  
25 angle is about 90E.

39. The device of claim 35 in which a localizing array is disposed proximate to an ear fitting.

30 40. The device of claim 35 in which the reference elements comprise radiographically opaque or semi-opaque material.

41. The device of claim 40 in which the material  
35 comprises steel or doped water.

42. The device of claim 35 which further comprises a securing means that facilitates the securing of the frame to the subject.

5

43. The device of claim 42 in which the securing means comprises an inelastic or elastic component and facilitates the securing of the frame to the head of the subject.

10 44. The device of claim 26 in which the one or more localizing arrays provide one or more signals that are detectable by MR, CT, PET, SPECT, EEG, or MEG.

15 45. The device of claim 26 in which the imager detectable signals are provided by a digitizer used in conjunction with the one or more localizing arrays.

20 46. A method of spatially aligning at least two radiographic scan images of the head of a subject taken by a radiographic scanning device comprising:

(a) radiographically scanning the head of a subject wearing the stereotactic device of claim 1 to provide a first radiographic scan image containing a plurality of first reference points defining a first personal coordinate system;

25 (b) relating said first personal coordinate system with a personal coordinate system obtained from a prior radiographic scan of said subject reproducibly wearing said stereotactic device;

(c) adjusting said radiographic scanning device to align  
30 said first and prior personal coordinate systems;

(d) obtaining one or more additional radiographic scans of said subject with the adjusted radiographic scanning device.

Fig. 1A

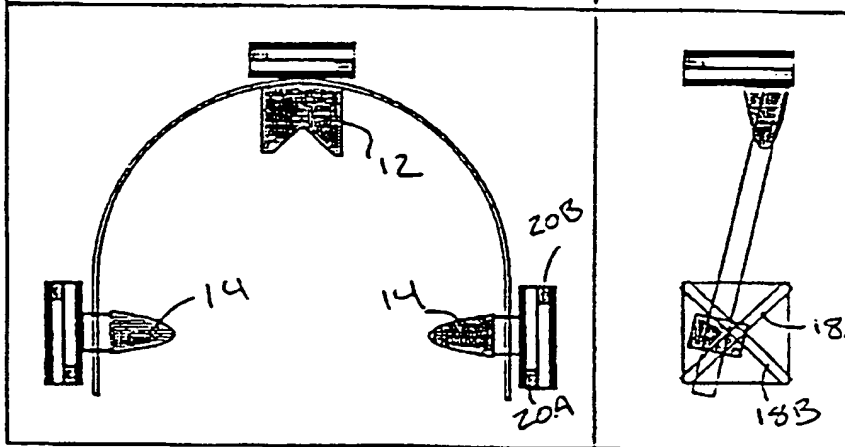
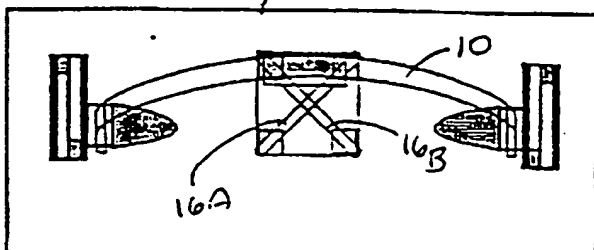


Fig 1B

Fig 1C

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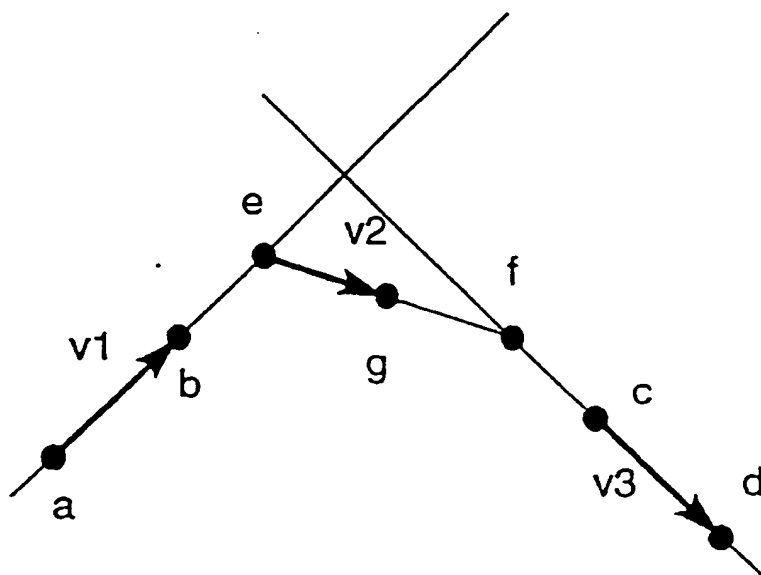
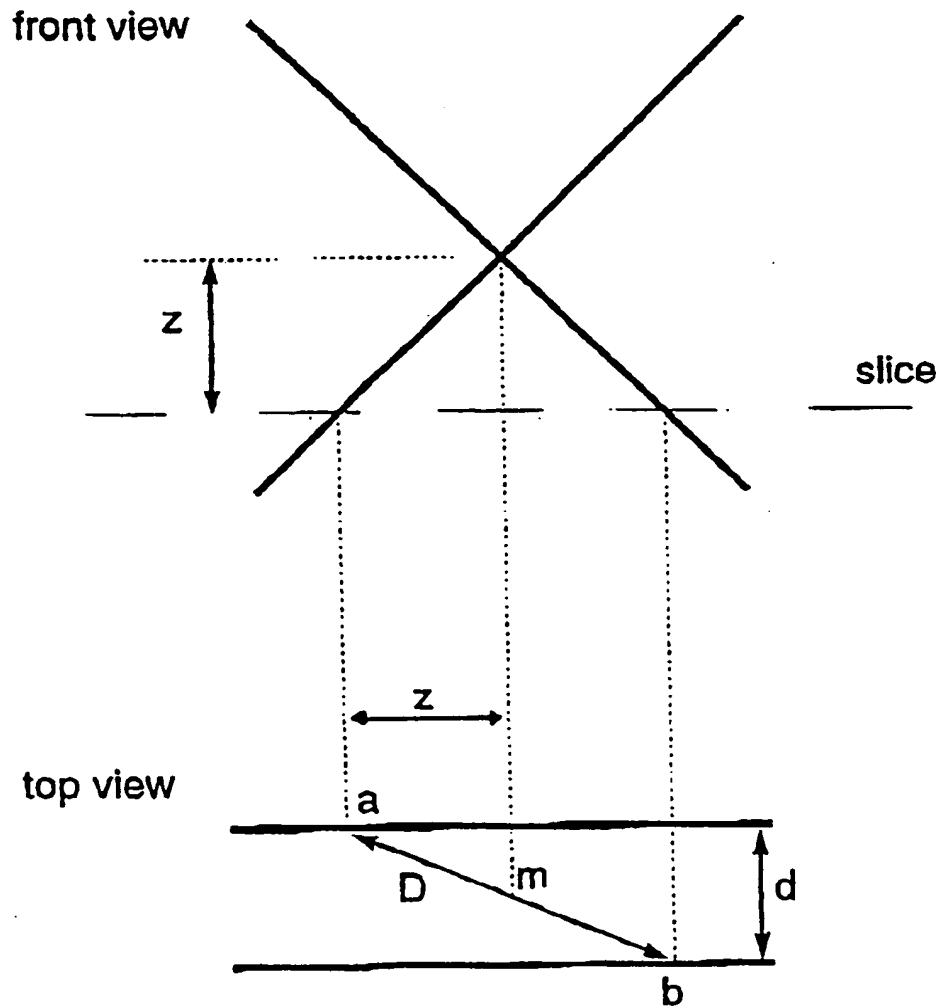


Fig 2.

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front view



top view

Fig 3

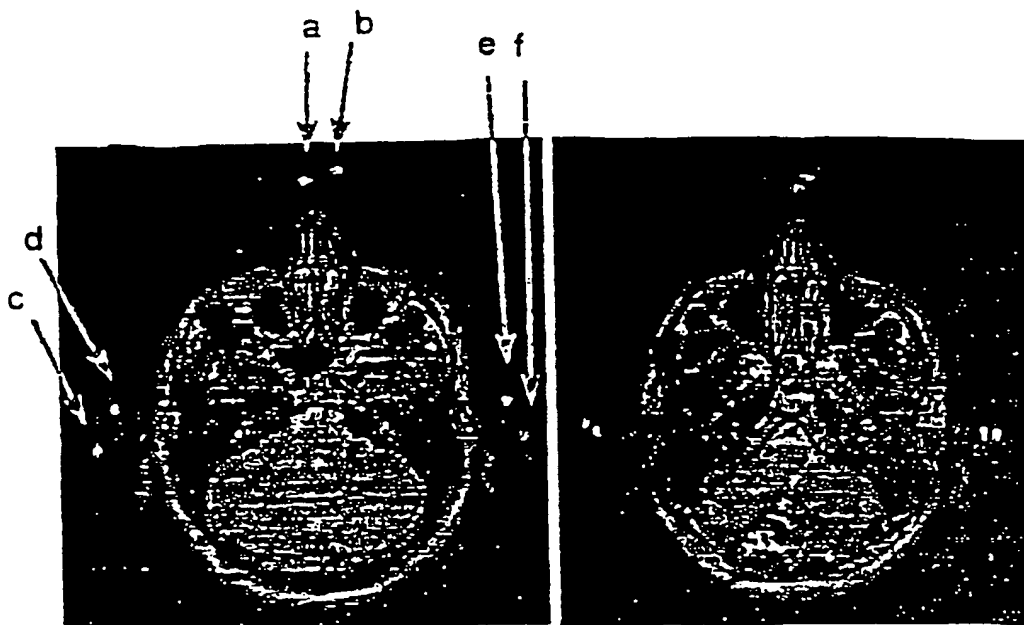


Fig. 4A

Fig. 4B

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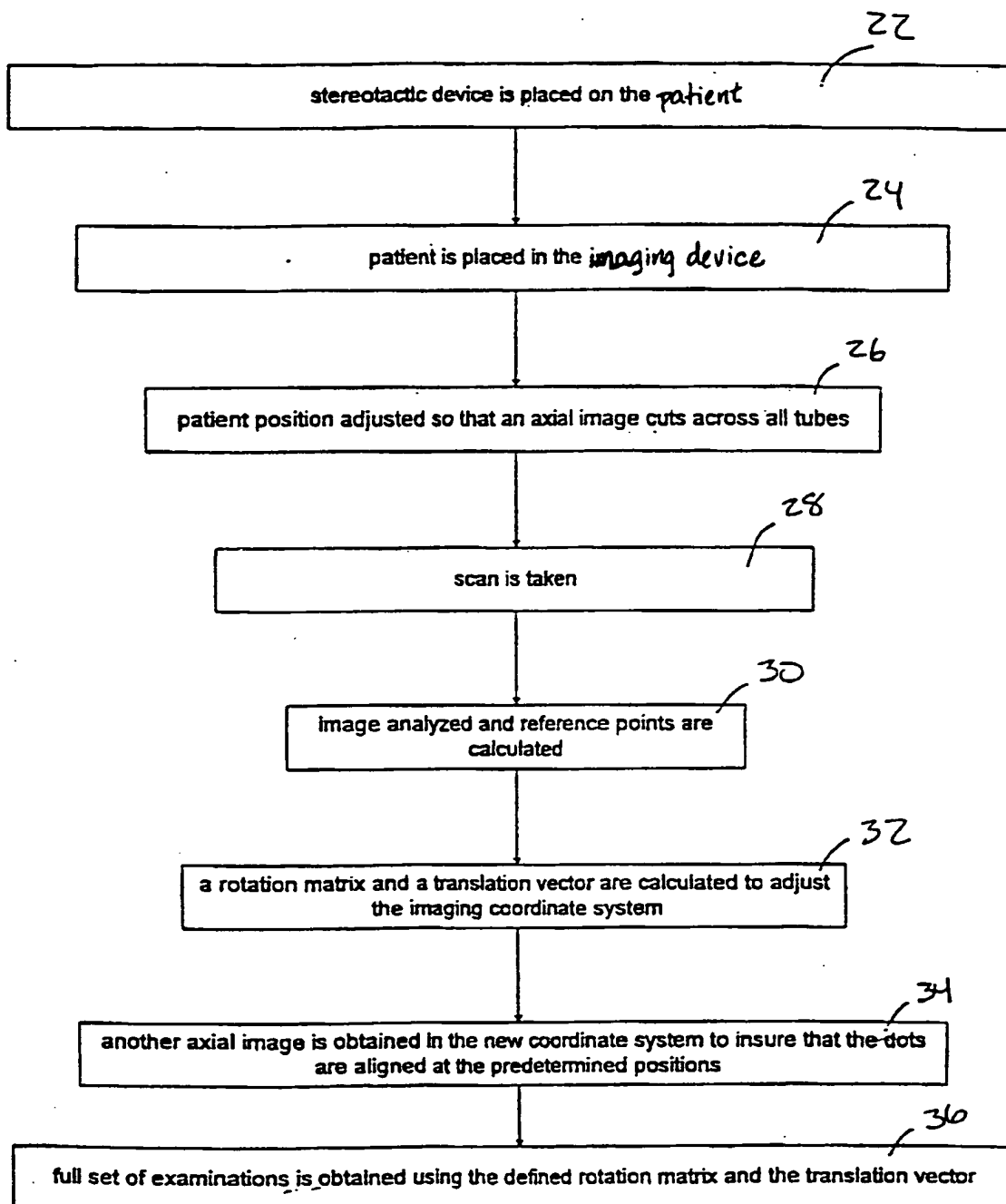


FIGURE 5



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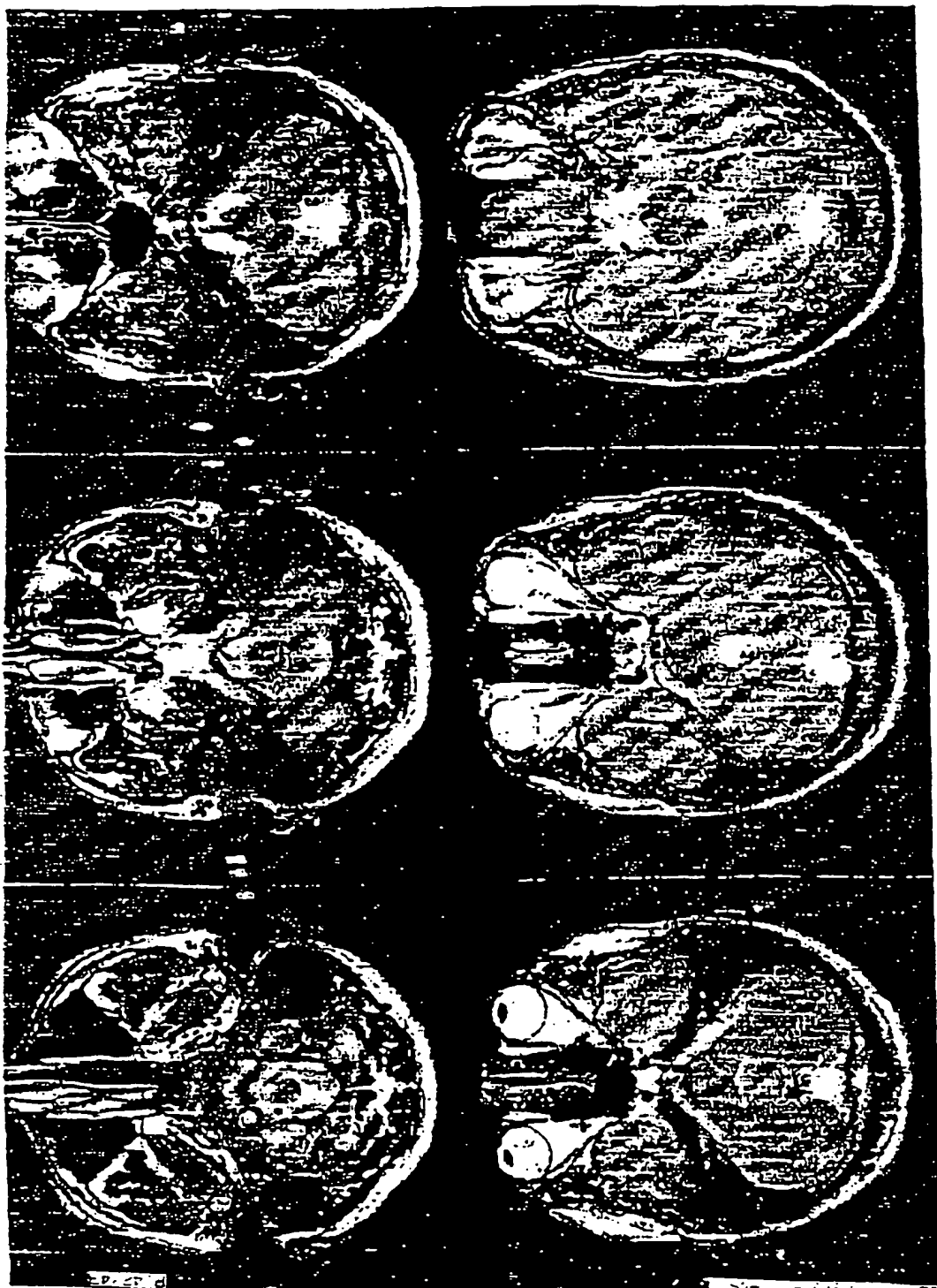


Fig 6A

Fig 6A

Fig 6A

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Fig 6B

Fig 6B

Fig 6B

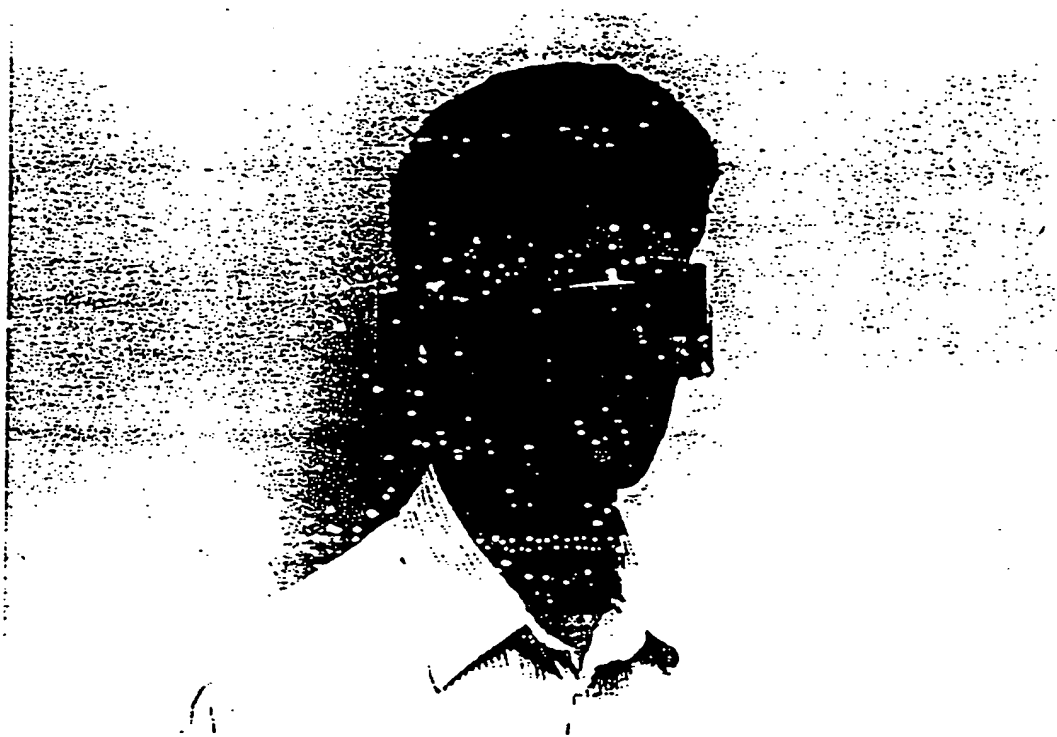


Fig. 7

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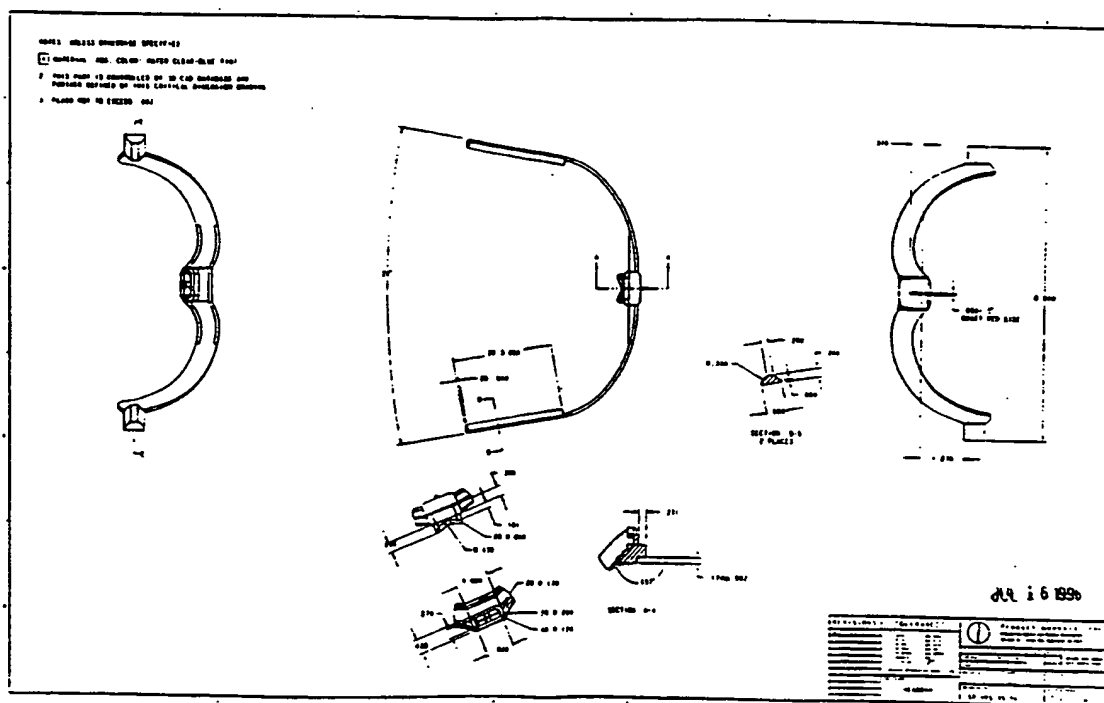


Fig. 8A

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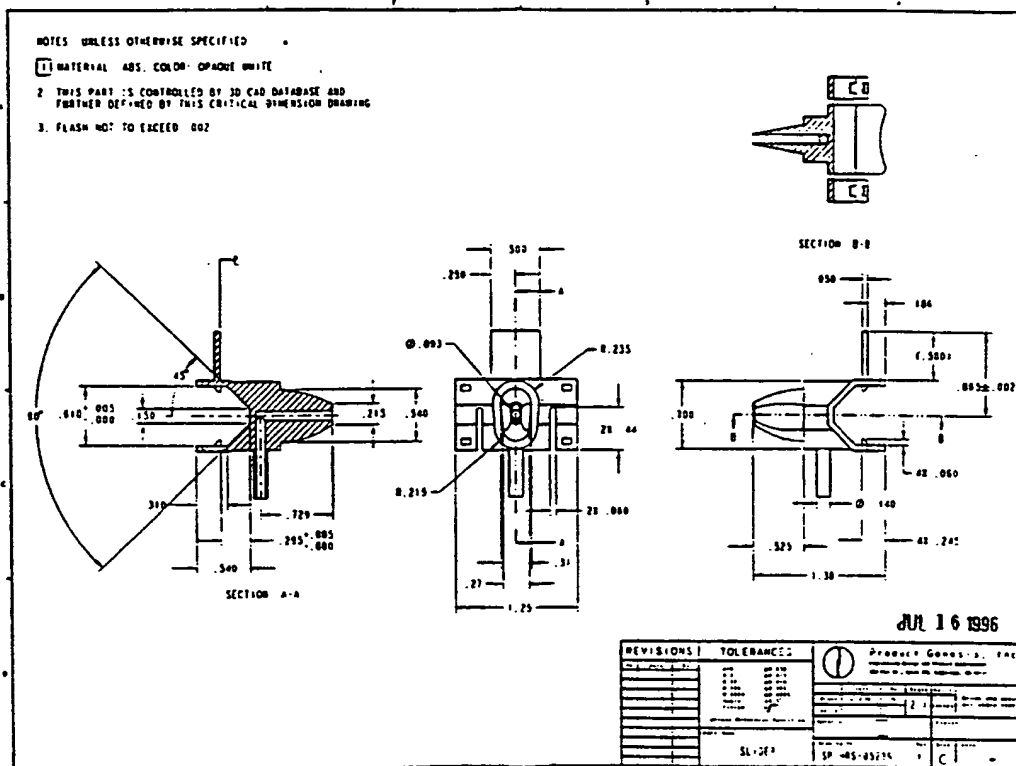


Fig. 8B





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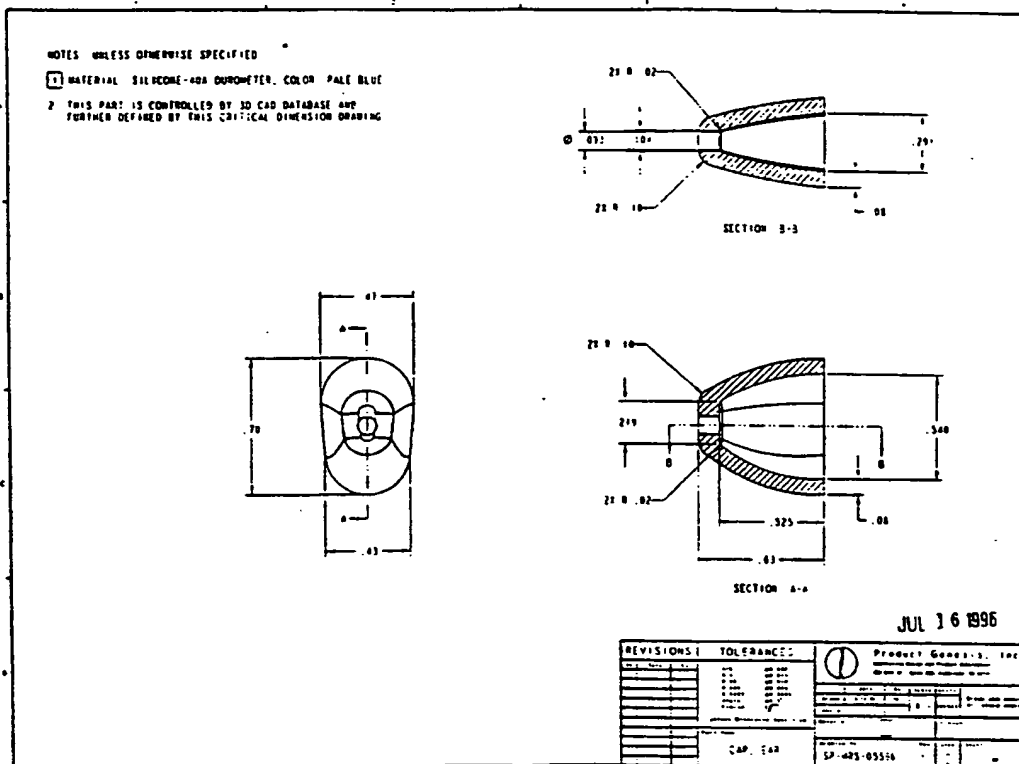


Fig. 8E



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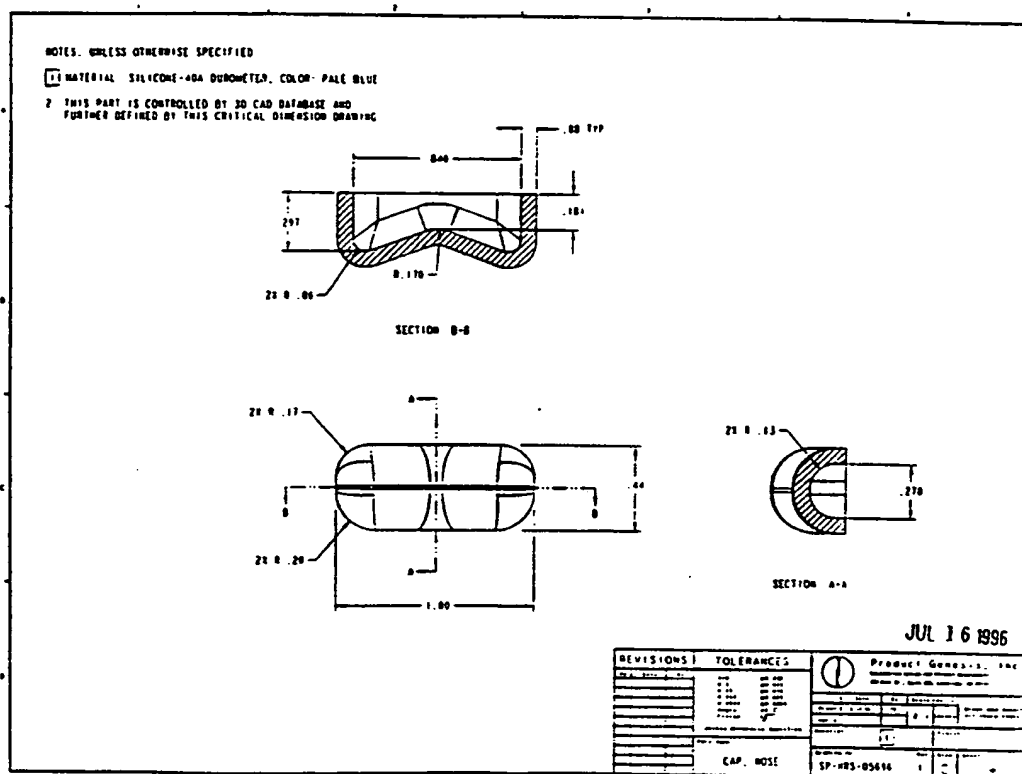


Fig. 8F

# INTERNATIONAL SEARCH REPORT

International application No.  
PCT/US96/13956

## A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :A61B 19/00

US CL :606/130

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 128/653.1, 543.2, 653.4; 606/1, 129, 130

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

Please See Extra Sheet.

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y, P	US 5,531,227 A (SCHNEIDER) 02 July 1996, col. 4, line 35, and all the figures.	1-25, 46.
Y	US 5,398,684 A (HARDY) 21 March 1995, col. 6, line 25 to col. 13, line 40, and Figs. 1, and 2.	1-5, 7-14, 17, 18.
X --- Y	US 4,923,459 A (NAMBU) 08 May 1990, the entire document.	26, 27, 30, 32, 44 ----- 6, 15, 16, 19-25, 28, 29, 31, 33-43, 45, 46.

☒ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

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Date of the actual completion of the international search

07 NOVEMBER 1996

Date of mailing of the international search report

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Facsimile No. (703) 305-3590

Authorized officer

JUSTINE R. YU

Telephone No. (703) 308-2675

## INTERNATIONAL SEARCH REPORT

International application No.  
PCT/US96/13956

## C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 4,618,978 (COSMAN) 21 October 1986, col.1, line 7 to col. 6, line 24, and Figs. 2A-7.	28, 29, 31, 33, 34, 37, 38, 40, 41
Y	US 5,263,494 A (MARGELOS et al) 23 November 1993, col. 1, line 6 to col. 11, line 63, and Figs. 1, 2, and 6.	35, 36, 39, 42, 43.

## INTERNATIONAL SEARCH REPORT

International application No.  
PCT/US96/13956

### B. FIELDS SEARCHED

Electronic data bases consulted (Name of data base and where practicable terms used):

APS

search terms: Imager and scan, superimpose, reprodu?, localiz?, machine coordinate system, non-invasive stereotactic, opaque, stereotactic.

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